NASA Technical Memorandum 81972

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DECEMBER 1981

NASA

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Scientific and Technical
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1981

SUMMARY

A flight test was conducted for preliminary evaluation of an aileron-rudder interconnect (ARI) control system for the F-14A airplane in the landing configuration. Two ARI configurations were tested in addition to the standard F-14 flight control system. Flight data and pilot comments were used to compare the effects of each control system on airplane lateral-directional handling qualities during a final-approach-course correction maneuver.

Results of the flight test showed marked improvement in handling qualities when the ARI systems were used. Sideslip due to adverse yaw was considerably reduced, and airplane turn rate was more responsive to pilot lateral-control inputs. Pilot comments substantiated the flight data and indicated that the ARI systems were superior to the standard control system in terms of pilot capability to make lateral offset corrections and heading changes on final approach.

INTRODUCTION

In cooperation with the Department of the Navy, the Langley Research Center and the Dryden Flight Research Center have conducted simulation and flight tests to investigate improvements to the handling characteristics of the F-14A airplane in the landing configuration. The study was undertaken as a result of fleet-pilot comments and quantitative flight data which indicated some undesirable lateral-directional handling qualities in the landing configuration. Specifically noted were the generation of a significant amount of adverse yaw following lateral stick inputs and a lightly damped Dutch roll mode, both of which made it difficult to control airplane heading precisely in a high-workload task such as a carrier landing.

A previous simulation study, described in reference 1, investigated the use of an aileron-rudder interconnect (ARI) system which involved extensive modifications to the roll and yaw control systems of the fleet airplane. Two ARI configurations were tested, and results were compared with those of the standard control system. Sideslip due to adverse yaw was considerably reduced by the ARI systems, and pilots were able to control heading more precisely.

The flight test described in this report was conducted to determine whether similar improvements in handling characteristics could be demonstrated during actual flight tests using the ARI systems. The test was conducted at the Dryden Flight Research Center by using an F-14A airplane modified with the experimental control systems.

SYMBOLS

All aerodynamic data and flight motions are referenced to the body system of axes shown in figure 1. The units for physical quantities used herein are presented both in the International System of Units (SI) and in U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units. Conversion factors for the two systems are given in reference 2.

a_Y lateral acceleration, positive along positive Y body axis, g units

g acceleration due to gravity ($1g = 9.8$ m/sec^2), m/sec^2 (ft/sec^2)

I_X, I_Y, I_Z moments of inertia about X, Y, and Z body axes, respectively, kg-m^2 (slug-ft^2)

I_{XZ} product of inertia with respect to X and Z body axes, kg-m^2 (slug-ft^2)

M_i indicated Mach number

p airplane roll rate about X body axis, deg/sec or rad/sec

q airplane pitch rate about Y body axis, deg/sec or rad/sec

r yaw rate about Z body axis, deg/sec or rad/sec

s Laplace variable, 1/sec

u,v,w components of airplane velocity along X, Y, and Z body axes, respectively, m/sec (ft/sec)

V airplane resultant velocity, m/sec (ft/sec)

V_i indicated airspeed, knots

X,Y,Z airplane body axes (see fig. 1)

α angle of attack, deg

α_{bias} signal used to bias α_i in ARI control systems, deg

α_e effective angle of attack, $\alpha_i + \alpha_{bias}$, deg

α_i indicated angle of attack, deg

β angle of sideslip, deg

δ_a differential horizontal-tail deflection, positive for right roll, deg

δ_h symmetric horizontal-tail deflection, positive for airplane nose-down control, deg

$\delta_{h,DLC}$ incremental horizontal-tail deflection due to DLC control inputs, positive for airplane nose-down control, deg

$\delta_{h,p}$ symmetric horizontal-tail deflection commanded by pilot longitudinal stick deflection, positive for airplane nose-down control, deg

δ_{ped} rudder-pedal deflection, positive for right yaw, cm (in.)

δ_r rudder deflection, positive for left yaw, deg

$\delta_{s,p}$ pilot longitudinal stick deflection, positive for pitch-up, cm (in.)

$\delta_{s,r}$ pilot lateral stick deflection, positive for right roll, cm (in.)

$\delta_{sp,DLC}$ symmetric spoiler deflection (both wings) due to DLC control inputs, positive for upward deflection, deg

$\delta_{sp,L}$ left-wing spoiler deflection due to lateral stick inputs, positive for upward deflection, deg

$\delta_{sp,R}$ right-wing spoiler deflection due to lateral stick inputs, positive for upward deflection, deg

$\left(\delta_{sp,L}\right)_T$ total left-wing spoiler deflection, positive for upward deflection, deg

$\left(\delta_{sp,R}\right)_T$ total right-wing spoiler deflection, positive for upward deflection, deg

δ_{TW} DLC thumbwheel deflection, positive for aft deflection, deg

ϕ Euler angle, deg

Abbreviations:

AGL above ground level

ARI aileron-rudder interconnect

DLC direct lift control

LSRI lateral-stick-to-rudder interconnect

SAS stability augmentation system

DESCRIPTION OF AIRPLANE

The F-14A is a two-place, twin-engine, jet fighter airplane having a variable-sweep wing and twin vertical tails. A photograph of the test airplane is shown in figure 2. In the landing configuration wing sweep is fixed at 20°, whereas in the maneuvering configuration sweep varies from 20° for low subsonic speeds to 68° for higher speed flight. Each wing is configured with leading-edge slats, trailing-edge flaps, and four upper surface spoiler panels. Figure 3 shows details of the wing flap, slat, and spoiler arrangements. In the landing configuration, leading-edge slats are deflected 17° and trailing-edge flaps are deflected full down to the 35° position; whereas the spoilers are normally raised to the 3° position. A speed brake on the upper and lower surfaces of the aft fuselage provides increased drag and allows the use of higher engine thrust settings for the landing approach.

Empty weight of the airplane used in the flight tests was 198 084 N (44 531 lb). Fuel weight during the tests varied from 32 027 N (7200 lb) to 13 345 N (3000 lb). Table I lists the mass and dimensional characteristics of the airplane at a fuel weight of 17 793 N (4000 lb).

BASIC AIRPLANE FLIGHT CHARACTERISTICS

Fleet-Pilot Comments

The following summary of F-14 lateral-directional handling characteristics was obtained from interviews with several F-14 qualified Navy pilots, some with test-pilot experience. The pilots were asked to comment on airplane handling qualities during all phases of the approach and landing, particularly during day and night carrier approaches.

According to those interviewed, the handling-qualities problems in the landing configuration are primarily due to adverse yaw following lateral stick inputs and a lightly damped Dutch roll mode. These effects are apparent both in visual and instrument tasks. Unless the pilot applies a generous amount of coordinating rudder, there is substantial adverse yaw both rolling into and out of turns. The adverse yaw and resultant heading excursions cause difficulty both in holding a specific heading and in making precise lineup corrections during an approach. The result is that pilot work load, already heavy because of the difficulty of a carrier approach, increases considerably because of the adverse control and damping characteristics.

Although the problems exist in all phases of the approach, the primary area of concern is from an altitude of approximately 61 m (200 ft) down to touchdown, since small lineup errors become important and pilot gain goes up considerably in the terminal phase of the approach and touchdown. Turbulence adds a further level of difficulty to the problems.

Flight Data

Analysis of flight data in the landing configuration tends to reinforce the qualitative pilot comments. Figure 4 shows the response of the F-14 test airplane to a lateral stick input applied to perform a bank-angle reversal from 30° to -50°. Rudders were not used. Note that a step lateral stick input of approximately 1.9 cm (0.75 in.) resulted in a 12° sideslip angle (β) which reached peak amplitude 3.0 sec after the lateral-control input. Note also the 1.5-sec delay in yaw-rate response (r) before the airplane began to turn in the proper direction; furthermore, the initial response appears to be opposite to the direction of stick input. Both of these characteristics contribute greatly to difficulties in precise heading control and tend to substantiate the pilot comments.

To eliminate effects of the stability augmentation system (SAS), both the roll and yaw SAS were disengaged for the test shown in figure 4. As a result, the Dutch roll motions are more lightly damped than motions the airplane would exhibit if the SAS system were engaged. However, the adverse yaw characteristics of the F-14 are essentially identical whether the SAS is engaged or disengaged.

DESCRIPTION OF FLIGHT CONTROL SYSTEMS

Basic System

The basic flight control system of the flight-test airplane, designated control system A in this report, was identical to fleet F-14 systems. The system consisted of mechanical linkages, spring and bobweight feel devices, hydraulic actuators, and a stability augmentation system (SAS). The SAS functions were generated by roll, pitch, and yaw computers which responded to inputs from the pilot's controls and various stabilization sensors. The computer outputs were fed through SAS actuators which drove the control-system mechanical linkages to produce surface motions. The SAS inputs were in series with pilot inputs and did not produce control-stick motion.

Pitch control.- Figure 5 shows a schematic diagram of the longitudinal (pitch) channel of the airplane. Pilot inputs at the stick provided a direct mechanical input to the all-movable horizontal tail (stabilizer). A washed-out pitch-rate feedback signal provided stability augmentation. The two inputs combined to produce symmetric stabilizer deflections (δ_h) over a range from 10° to -33°. The pitch SAS had an authority limit of ±3° deflection, and deflection rates were limited to 20 deg/sec.

Direct-lift control.- For improved flight-path-angle response, the pilot could select direct lift control (DLC) with the control-stick DLC switch. A thumbwheel, also located on the control stick, provided for DLC inputs and was spring loaded to the neutral position. When DLC was engaged, all spoilers extended 3° above the cruise zero-deflection position. (See fig. 3.) Forward rotation of the thumbwheel extended the spoilers and aft rotation retracted them according to the schedule shown in figure 6.

The trailing edges of the horizontal stabilizers were displaced 6° downward from their trim position when DLC was engaged in order to compensate for the change in pitching moment due to spoiler extension. (See fig. 6.) When the thumbwheel control was rotated fully forward, the spoilers extended to the 12° position and the stabilizer trailing edges were displaced 8° down. This action increased the rate of descent. When the thumbwheel control was rotated fully aft, the spoilers retracted to the -4.5° position and the stabilizer trailing edges returned to the trim position. This action decreased the rate of descent.

If DLC was not selected, all the spoilers were deflected 4.5° downward from their cruise zero-deflection position when trailing-edge flaps extended beyond 25°. (See fig. 3.) In this mode of operation, spoilers were used only for roll control.

Lateral control.- The lateral-control system used a combination of differential horizontal-stabilizer deflection and spoiler deflection for roll control. Figure 7 shows a schematic diagram of the roll channel. Without roll SAS engaged, δ_a deflection was controlled solely by mechanical inputs from the control stick and had a maximum deflection of ±7°. When roll SAS was engaged another ±5° deflection was provided through a series actuator, which received electrical inputs from a lateral-control stick-deflection sensor and stabilization signals from the roll gyro.

Whether roll SAS was engaged or disengaged, spoilers were used to assist roll control and were actuated via electrical signals from a lateral stick-deflection sensor. Figure 8 shows a schematic diagram of the spoiler control system, including both roll and DLC inputs. Lateral-stick-to-spoiler gearing schedules, which were a function of whether DLC was engaged or disengaged, are shown in figure 9.

Directional control.- Conventional rudders on each vertical tail were used for directional control. Figure 10 shows a schematic diagram of the yaw channel of the airplane. Full rudder authority (±30°) was available to the pilot through a mechanical linkage to the rudder pedals. With yaw SAS engaged, stabilization signals from a yaw rate gyro and lateral accelerometer were blended with pilot rudder inputs.

Experimental Systems

The ARI control systems which were evaluated in the current flight test resulted from modifications to a high-angle-of-attack (α) ARI design which is described in references 3 and 4. The high-α system was developed by the Langley Research Center to improve stability and control characteristics of the F-14 during high-α maneuvering. A subsequent simulator study (ref. 1) examined the feasibility of applying these ARI concepts to the landing configuration, and at the conclusion of that study two ARI configurations were selected for flight evaluation. Designated control system B and control system C, the ARI configurations represented two different levels of modification to the roll and yaw channels of the high-α ARI design. The pitch channel, however, remained unchanged and was identical in all three control systems flown (A, B, and C).

Control system B.- The ARI system, shown schematically in figures 11 and 12, featured several modifications to the roll and yaw channels, respectively, of control system A. The primary modifications to the roll channel were as follows: (1) a provision to fade out differential tail deflection due to lateral stick inputs as angle of attack increased, and (2) increased roll-rate damping. The yaw channel also featured the following two modifications: (1) a lateral-stick-to-rudder (LSRI) interconnect gain to counteract adverse yaw automatically, and (2) a roll-rate feedback to increase lateral-directional damping.

The angle-of-attack and Mach scheduling features of the ARI were designed to improve the handling qualities of the airplane during high-α maneuvering and to reduce the probability of control-induced spin entries. However, at approach and landing conditions ($\alpha_i = 12°$), these ARI features were ineffective. In order to utilize the ARI during landing it was necessary to bias the airplane indicated angle-of-attack signal (α_i), which was used as an input to the control systems. To accomplish this, a positive angle-of-attack bias signal ($\alpha_{bias} = 8.96°$) was summed with α_i to produce larger effective angle-of-attack values (α_e) that were then used as inputs to the α schedules. As a result, ARI features became effective at all airplane angles of attack above approximately 3° and, therefore, were active during the landing approach. The relationship between true angle of attack α and the angle of attack sensed by the test airplane α vane (α_i) is shown in figure 13. Note that approach and landing operations always occurred at $M_i \leq 0.55$ and, thus, the Mach scheduling feature did not vary control-system gains in the landing configuration.

Control system C.- For control system C the same value of α_{bias} was used as in control system B; however, several changes were made to the fixed gain values. Figure 14 shows the yaw channel of control system C. The only gain change from control system B was an increase in the LSRI gain from 2.60 to 3.19. This provided slightly more rudder for turn coordination and resulted in quicker yaw response for initiation of turns.

The roll channel of control system C is shown in figure 15. Two changes were made from control system B. First, the stick-to-differential-tail gain was slightly increased to match the increased LSRI gain. This was accomplished by moving the α breakpoints in the $\delta_a/\delta_{s,r}$ loop from 14° and 40° to 17° and 43°, respectively. The other gain change was an increase in the roll-rate damping multiplier from 4.0 to 5.0, which provided better damping to complement the increased LSRI and $\delta_a/\delta_{s,r}$ gains.

TEST PROCEDURES

The flight-test airplane was an F-14A which was modified to include the ARI systems described previously. By using cockpit switches, the pilot could select the basic F-14 control system (A) or either of the two ARI configurations (B or C). The airplane was flown by a NASA research test pilot, and the tests were conducted at the Dryden Flight Research Center, Edwards, California.

Since it was not possible to conduct actual carrier landings at the test site, it was difficult to achieve the level of task difficulty which would allow direct comparison of flight results with those of the simulation evaluation described in reference 1. It is generally recognized that carrier landings, especially at night, present a higher level of difficulty than runway landings since carrier approaches are flown to a touchdown point which is moving relative to the approaching airplane. Lateral lineup cues are quite different from those present in approaches to a runway, and the techniques used to accomplish the lineups are generally more demanding.

The flight-evaluation task was a series of 12 approaches flown to the primary runway at Edwards Air Force Base, California. In order to increase the task difficulty, the approaches were accomplished from a lateral offset on final approach. Landing gear, landing flaps, and speed brakes were extended for all approaches; DLC was also selected. From an altitude of 200 m (656 ft) AGL on downwind, the pilot began a 180° left descending turn to final approach while slowing to approach angle of attack. The turn to final approach was completed at approximately 100 m (328 ft) AGL and 2000 m (6562 ft) from the runway threshold. Laterally, the turn was completed by rolling out 25 m (82 ft) to the left of the runway center line, lining up on a painted stripe on the runway. This offset was maintained down to an altitude of 50 m (164 ft) AGL, at which point a lateral correction to center line was initiated. The lineup correction had to be made rapidly enough to enable landing on the runway center line at the nominal touchdown point (approximately 300 m (984 ft) from the threshold). Each approach was terminated at an altitude of 20 m (66 ft) AGL and no touchdowns were made. All approaches were flown in day visual-flight-rule (VFR) conditions.

The purpose of using the offset approaches was to require a maneuver which would identify lateral-directional handling deficiencies. The lateral correction to center line required the pilot to make a fairly rapid series of lateral stick inputs. Rudder-pedal inputs were used only when necessary to complete the maneuver.

A total of 12 offset approaches were flown, with 4 approaches in each control-system configuration. The sequence began with four approaches using control system B, followed by four approaches using control system A, and finally with four approaches using control system C.

Fuel weights during the first and last approach were 32 027 N and 13 345 N (7200 lb and 3000 lb), respectively. Since this involved only fuselage fuel tanks, changes in moments of inertia and center of gravity were negligible.

DISCUSSION OF RESULTS

Time histories are shown in figures 16, 17, and 18 for an offset approach with control systems A, B, C, respectively. Only one approach is shown for each control system. The three approaches selected were typical in terms of the results noted for each particular system.

Control System A

Figure 16 shows the time history of a typical approach with control system A. The time scale shown at the bottom of the figure represents elapsed time from an arbitrarily selected point prior to the offset correction maneuver. The point at which the pilot applied a lateral stick input to begin the correction to center line occurred at approximately 16 sec on the time scale. At that time the pilot applied a right lateral stick input of approximately 2.5 cm (1.0 in.) for 0.5 sec. This was followed by several control-stick inputs to stabilize the maneuver and to roll out with wings level on the runway center line. The maneuver lasted 12 sec, measured from the time the offset correction was initiated until the minimum altitude occurred which resulted in termination of the approach.

Analysis of the motions shows a noticeable lack of yaw-rate response for almost 3 sec after the initial control input, indicating adverse yaw. In addition, significant sideslip (β) excursions occurred throughout the maneuver which is indicative of both adverse yaw and a lightly damped Dutch roll mode. Pilot roll-control inputs, as well as roll and sideslip oscillations, were of significant magnitude throughout the maneuver.

Control System B

Figure 17 shows time-history results of an approach with control system B. The initial lateral input was very similar to that used on the previously described approach; however, the magnitude of subsequent inputs tended to decrease as the maneuver progressed. Following the application of lateral-control inputs, there was almost immediate yaw-rate response in the proper direction, and yaw oscillations were well damped throughout the maneuver. Very little sideslip occurred as a result of the control inputs. Since pilot rudder inputs were not used, these results indicate a favorable effect of the lateral-stick-to-rudder feature of the ARI design. During the 12-sec maneuver it is apparent that pilot roll-control inputs, as well as roll rate and sideslip oscillations, were smaller in magnitude and more damped than those of control system A.

Control System C

Figure 18 shows time-history results of an approach with control system C. The initial lateral-control input was smaller than in the previous two cases, but subsequent inputs were very similar to the case for control system B.

Airplane yaw-rate characteristics were approximately the same as that noted with system B in terms of response to controls and damping. However, the magnitude of yaw rate relative to size of control input was slightly higher than for control system B, because of the higher lateral-stick-to-rudder gain in control system C. The effect of this gain on rudder response is shown in the time-history traces for both control systems B and C. Sideslip-angle oscillations were very small throughout the maneuver and similar to the results noted for control system B. Also, pilot inputs and roll rate were well damped as with control system B.

Pilot Comments

The following statements are a summary of pilot comments which were made at a flight debriefing immediately following the completion of the test flight.

Control system A.- There was a distinct, dramatic difference in the airplane response between the basic control system (system A) and the ARI systems. The nose yawed back and forth excessively following lateral-control inputs with control system A. It was not possible to do the offset maneuver with feet on the floor because of the adverse yaw and lightly damped Dutch roll motions. After trying the first maneuver without using rudder pedals, the subsequent maneuvers were done with rudder-pedal assistance. There was significant adverse coupling between roll and yaw, making it difficult to control heading with lateral stick inputs. Thus, it was necessary to coordinate a large amount of rudder-pedal input to keep the nose turning in the proper direction.

Control system B.- The airplane response to controls was good and the lineup task was much easier with this system. It was not necessary to use rudder pedals for any part of the maneuver. The initial roll response was a little jerky, but this was true of each system tested including control system A.

Control system C.- Response to control inputs was very good and there were no objectionable qualities. Again, the use of rudder pedals was not necessary for the ARI system. Although the pilot did not encounter a lateral PIO (pilot-induced oscillation) with this system, there might possibly be a PIO problem with a real high-gain pilot because of the rapid roll and yaw response. Control system C did not seem dramatically better than control system B, but there was a tremendous improvement over control system A.

CONCLUDING REMARKS

A previous carrier-landing simulation study of the F-14A airplane concluded that an aileron-rudder interconnect (ARI) control system produced better handling qualities and improved pilot performance over the standard F-14A control system. The objective of the present flight-test program was to determine whether similar improvements in handling qualities could be demonstrated in a real airplane configured with the same control systems.

Although the approach task was different in the simulation and flight test, strong similarities were exhibited in the results and pilot comments. Flight-test results of the unmodified F-14A showed considerable adverse yaw, large sideslip excursions, and lightly damped Dutch roll oscillations. On the other hand, both ARI configurations tested provided a marked improvement in handling qualities as follows: airplane turn rate was more responsive to pilot lateral-control inputs, sideslip was reduced because of the coordinating rudder feature of the ARI, and the Dutch roll damping was significantly increased.

It is emphasized that the flight test conducted was of a very limited nature, so that no final conclusions can be drawn regarding the suitability of the ARI systems for actual carrier landings. However, the results showed that the ARI systems provided very definite improvements in handling qualities in areas where the basic airplane is known to be deficient. In order to investigate fully the improvements possible with the ARI systems, further flight tests should be conducted to optimize the systems and evaluate them during actual carrier landings.

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November 9, 1981

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4. Nguyen, Luat T.; Gilbert, William P.; Gera, Joseph; Iliff, Kenneth W.; and Enevoldson, Einar K.: Application of High-α Control System Concepts to a Variable-Sweep Fighter Airplane. AIAA-80-1582, Aug. 1980.

TABLE I.- MASS AND DIMENSIONAL CHARACTERISTICS OF TEST AIRPLANE

Weight with 17 793 N (4000 lb) of fuel, N (lb)	215 877 (48 531)
Moments of inertia, kg-m^2 (slug-ft^2):	
I_X	89 647 (66 120)
I_Y	360 217 (265 681)
I_Z	444 288 (327 689)
I_{XZ}	-3440 (-2537)
Wing dimensions:	
Span, m (ft)	19.55 (64.13)
Area, m^2 (ft^2)	52.5 (565)
Mean aerodynamic chord, m (ft)	2.99 (9.80)
Center of gravity, percent of mean aerodynamic chord	13.4

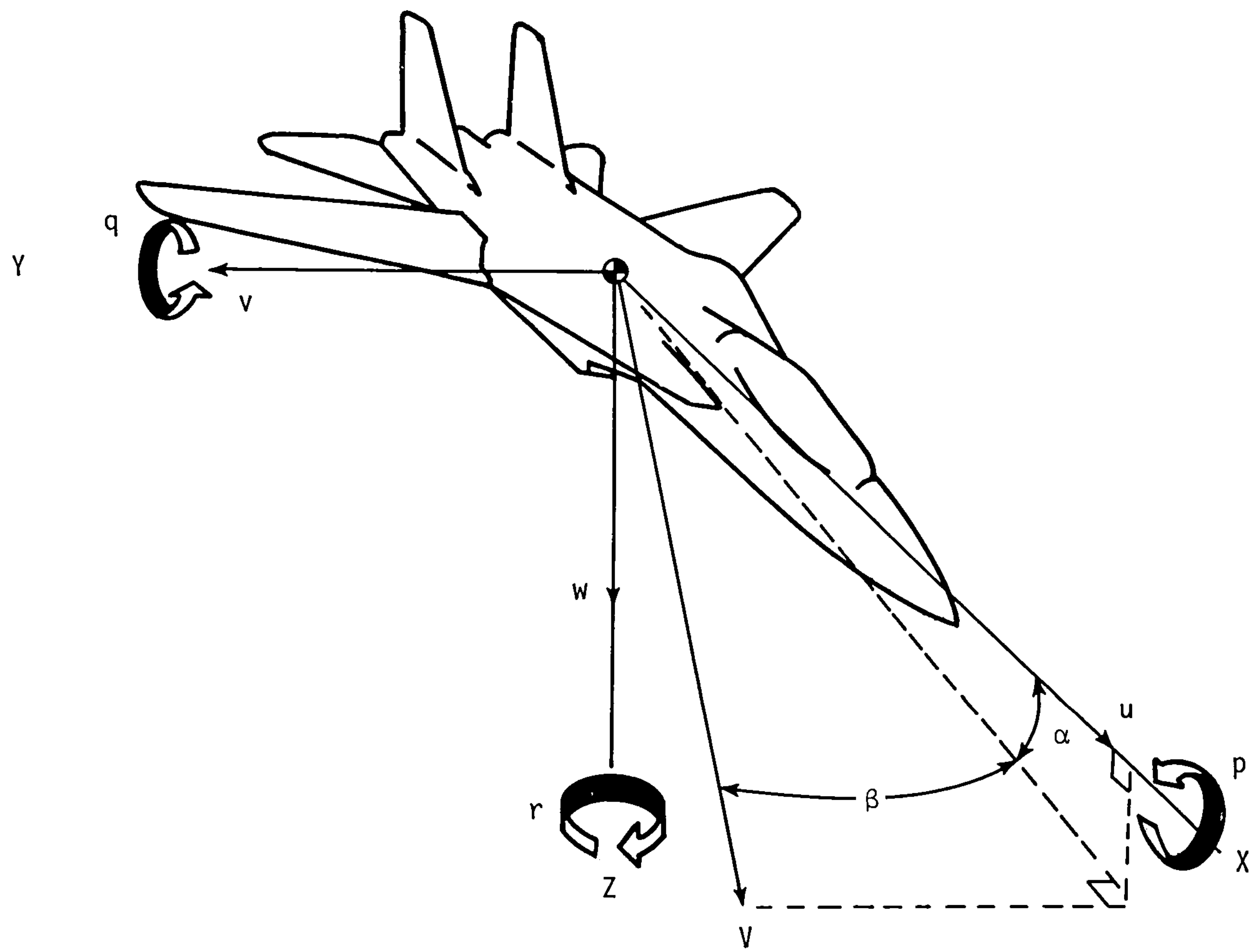

Figure 1.- The body system of axes.

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Figure 2.- Photograph of the F-14A flight-test airplane in the landing configuration.

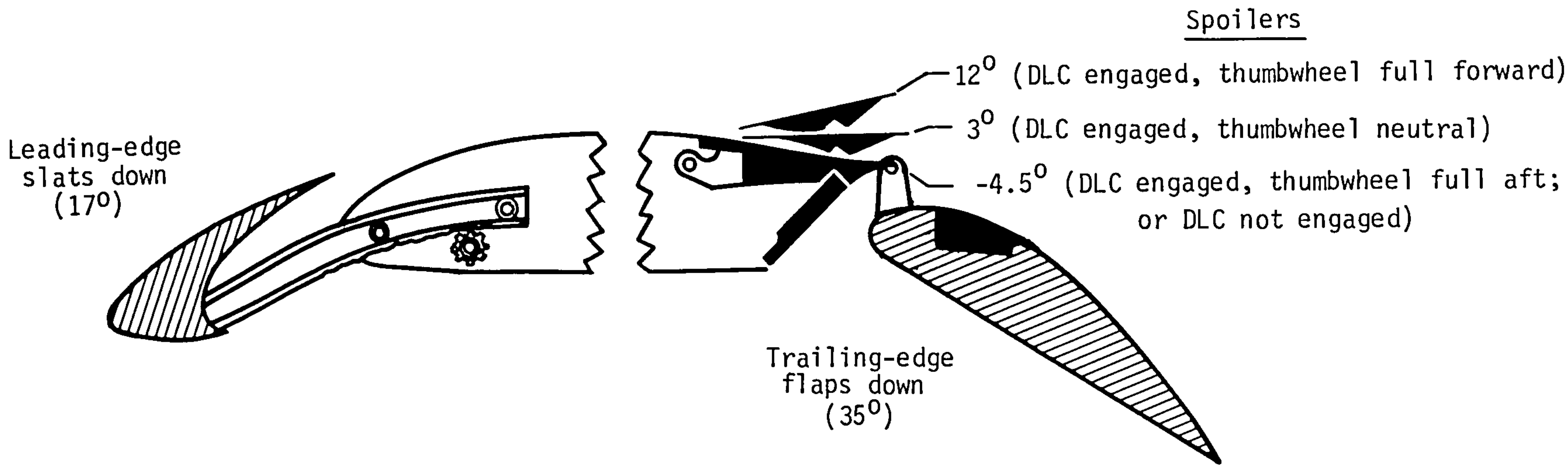


Figure 3.- Wing control surfaces.

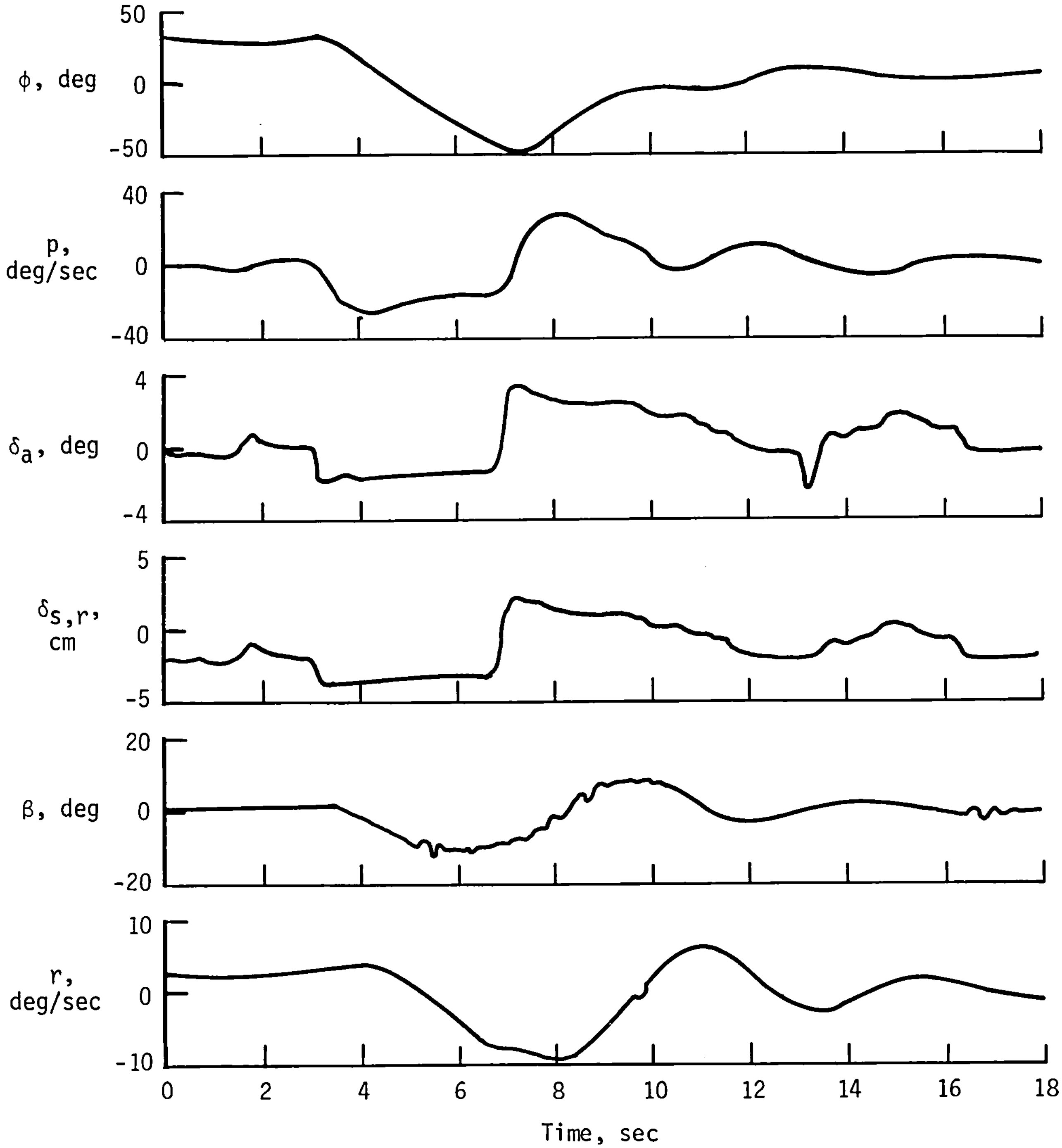


Figure 4.- Response of the F-14 test airplane to lateral stick input.

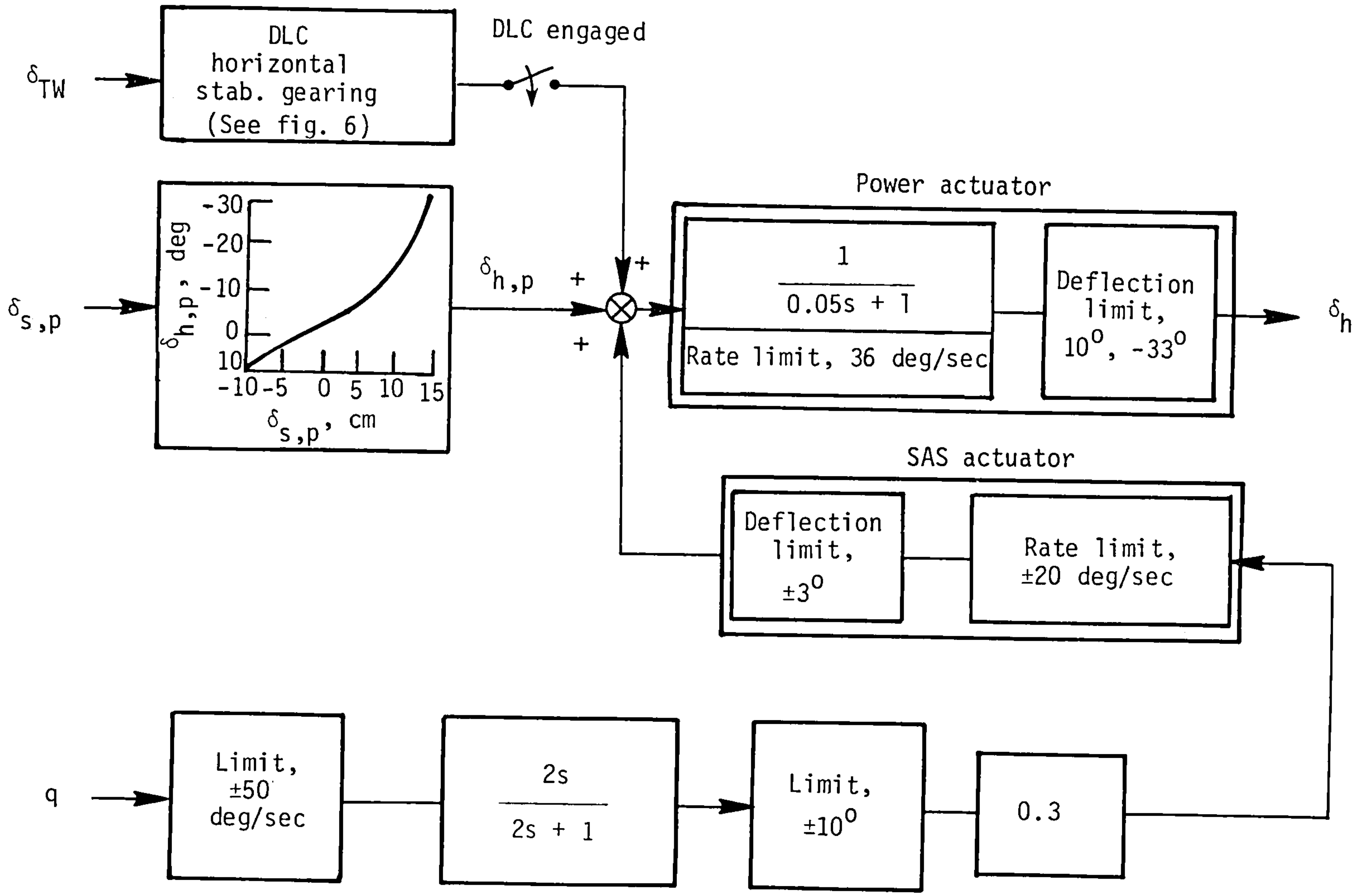
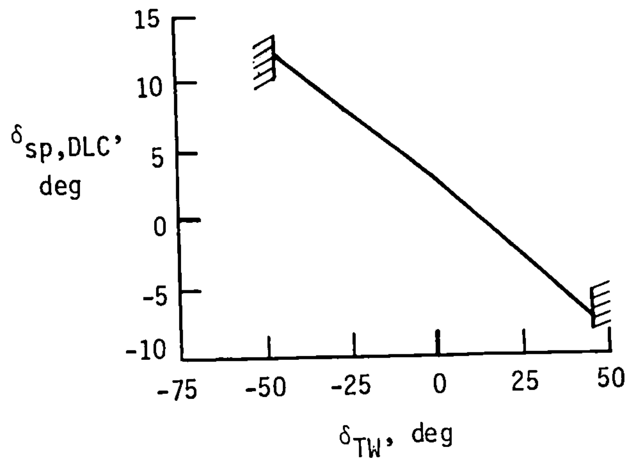
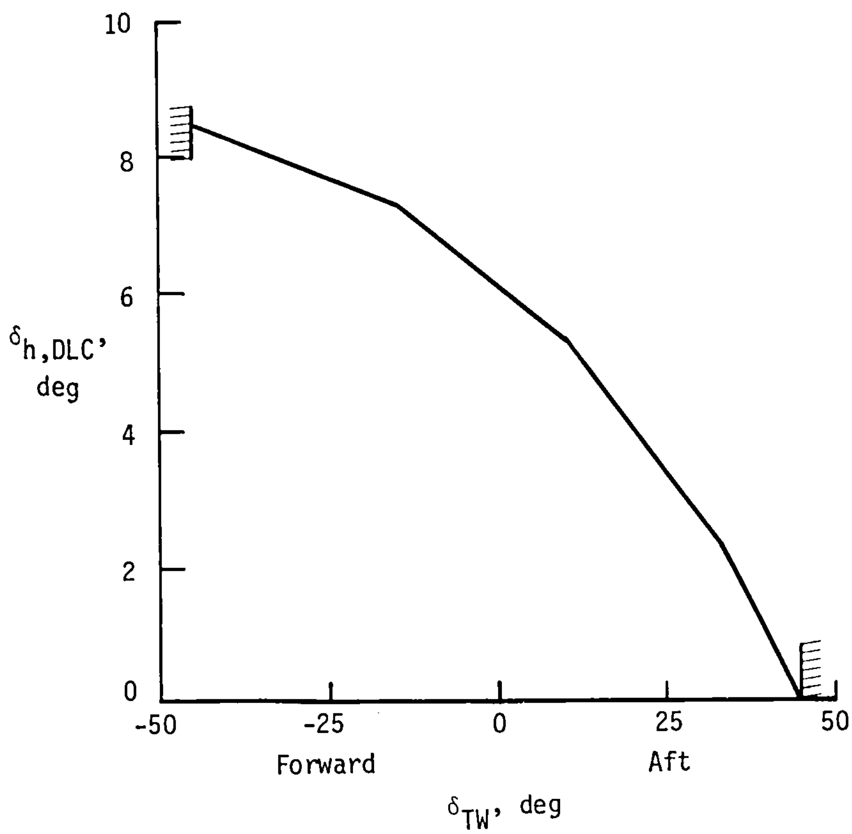


Figure 5.- Schematic diagram of pitch channel of all control configurations.



(a) Spoiler deflection as a function of DLC thumbwheel inputs.



(b) Horizontal-stabilizer deflection as a function of DLC thumbwheel inputs.

Figure 6.- Control-surface deflections for DLC operation.

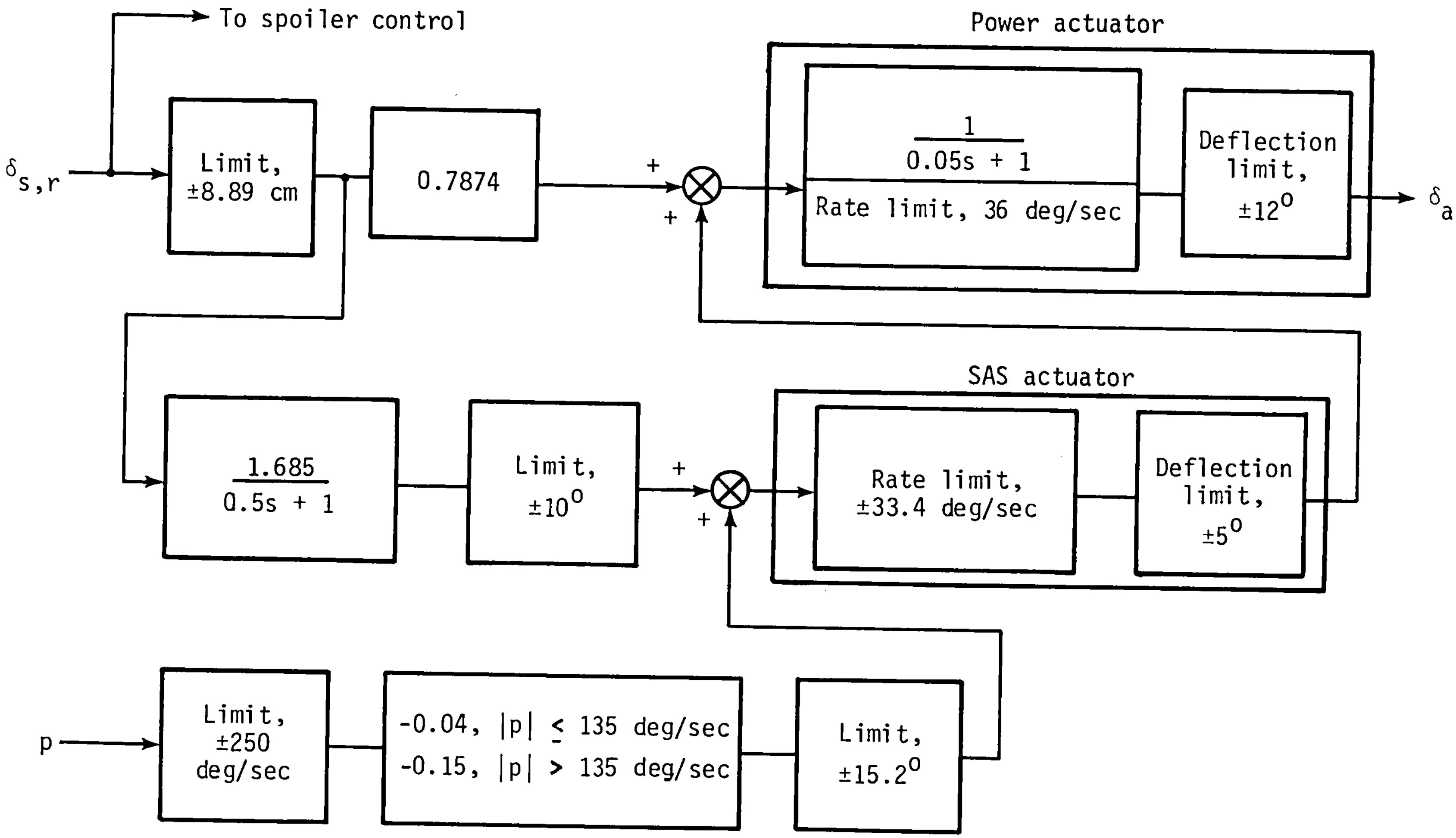


Figure 7.- Schematic diagram of roll channel of control system A.

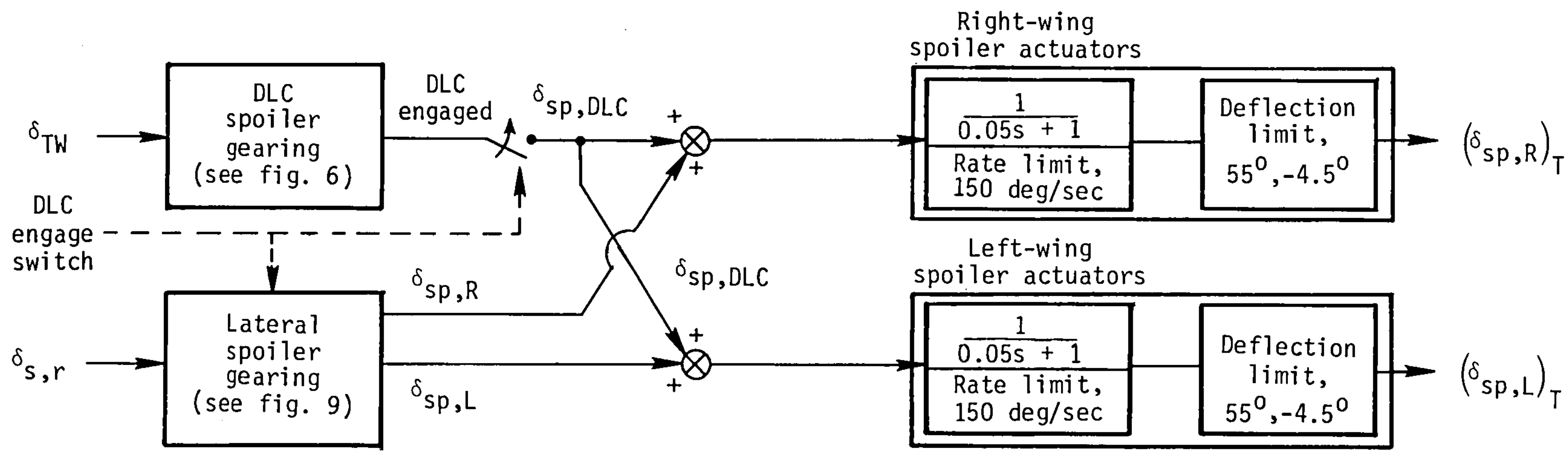
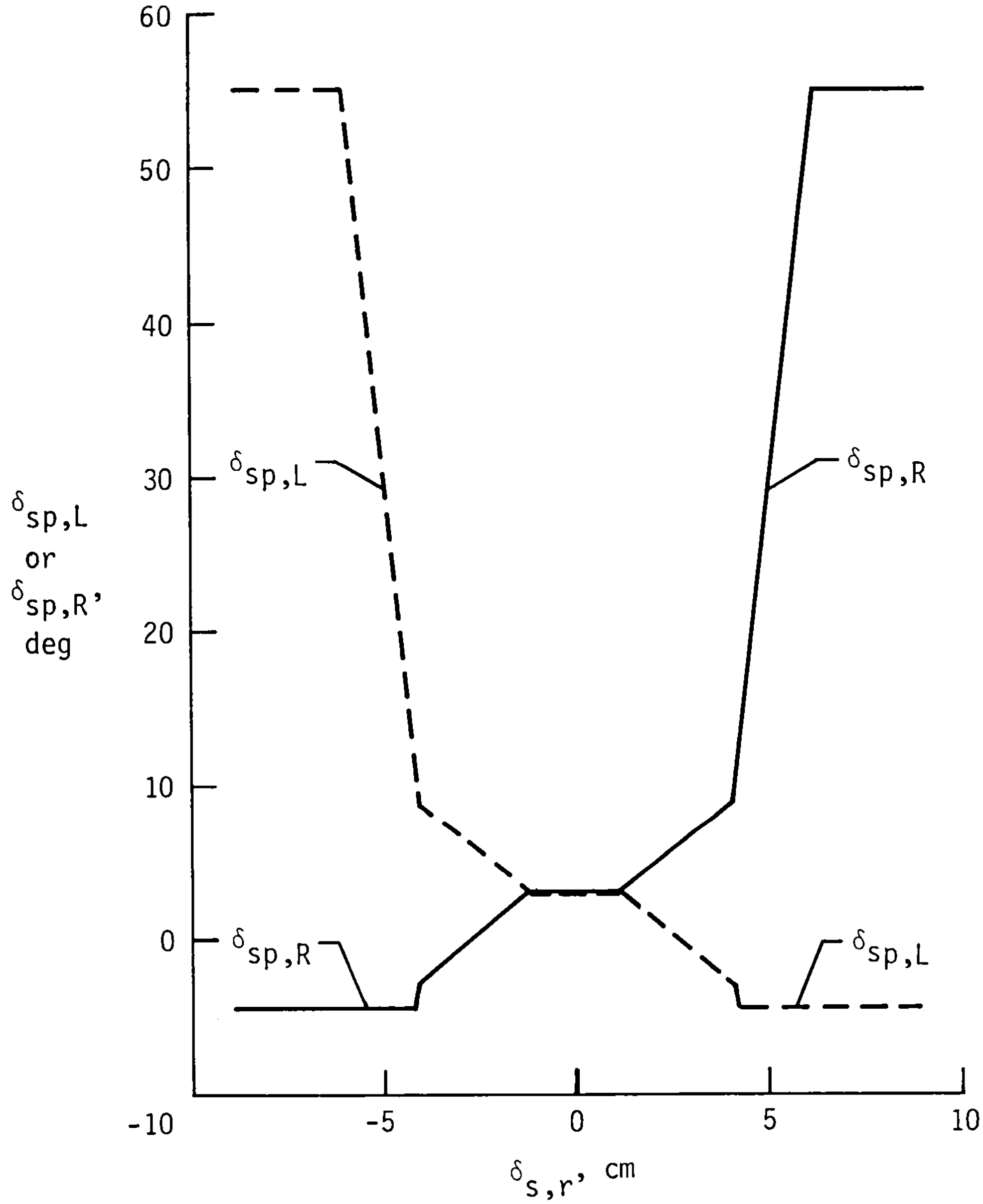
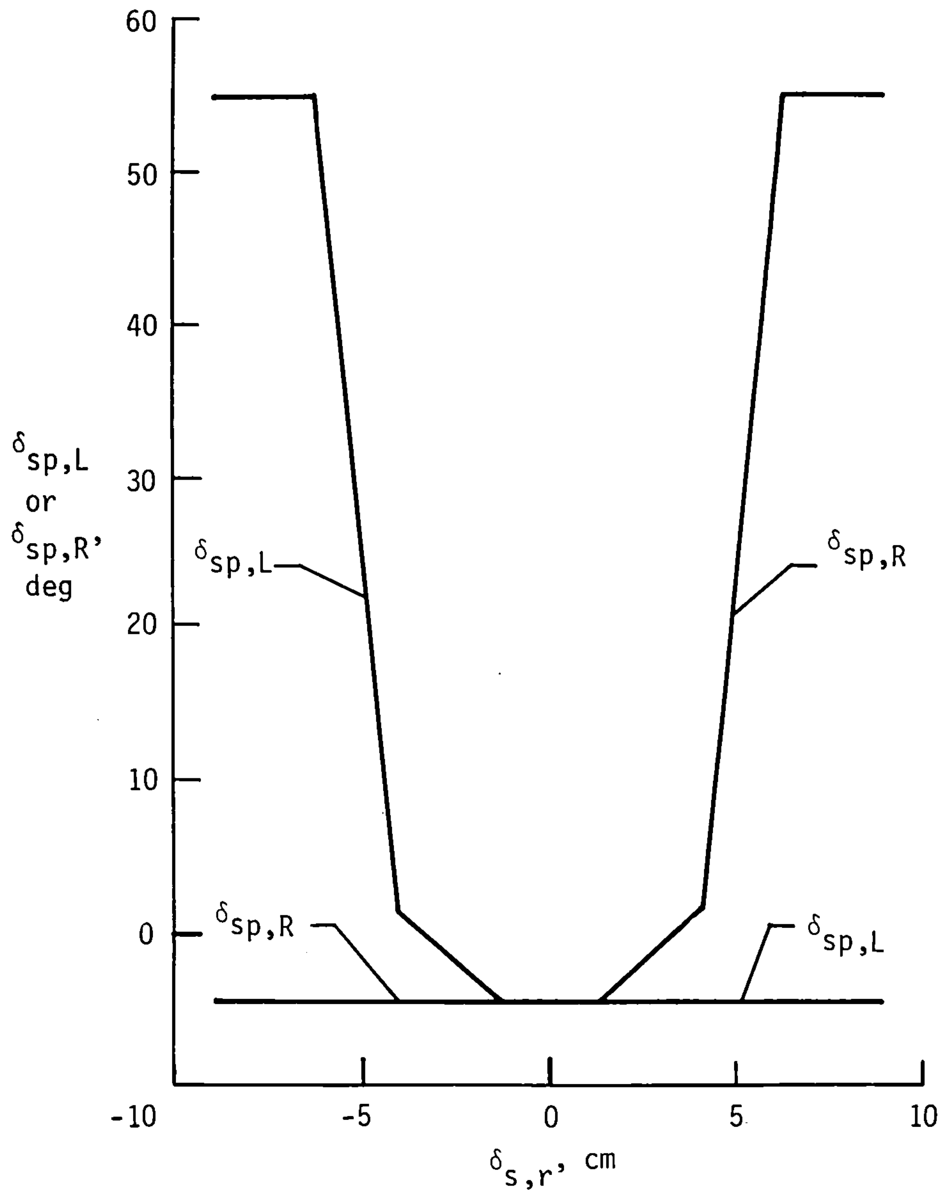


Figure 8.- Schematic diagram of spoiler control system of all control configurations.



(a) DLC engaged.

Figure 9.- Spoiler deflections as a function of lateral stick input.



(b) DLC not engaged.

Figure 9.- Concluded.

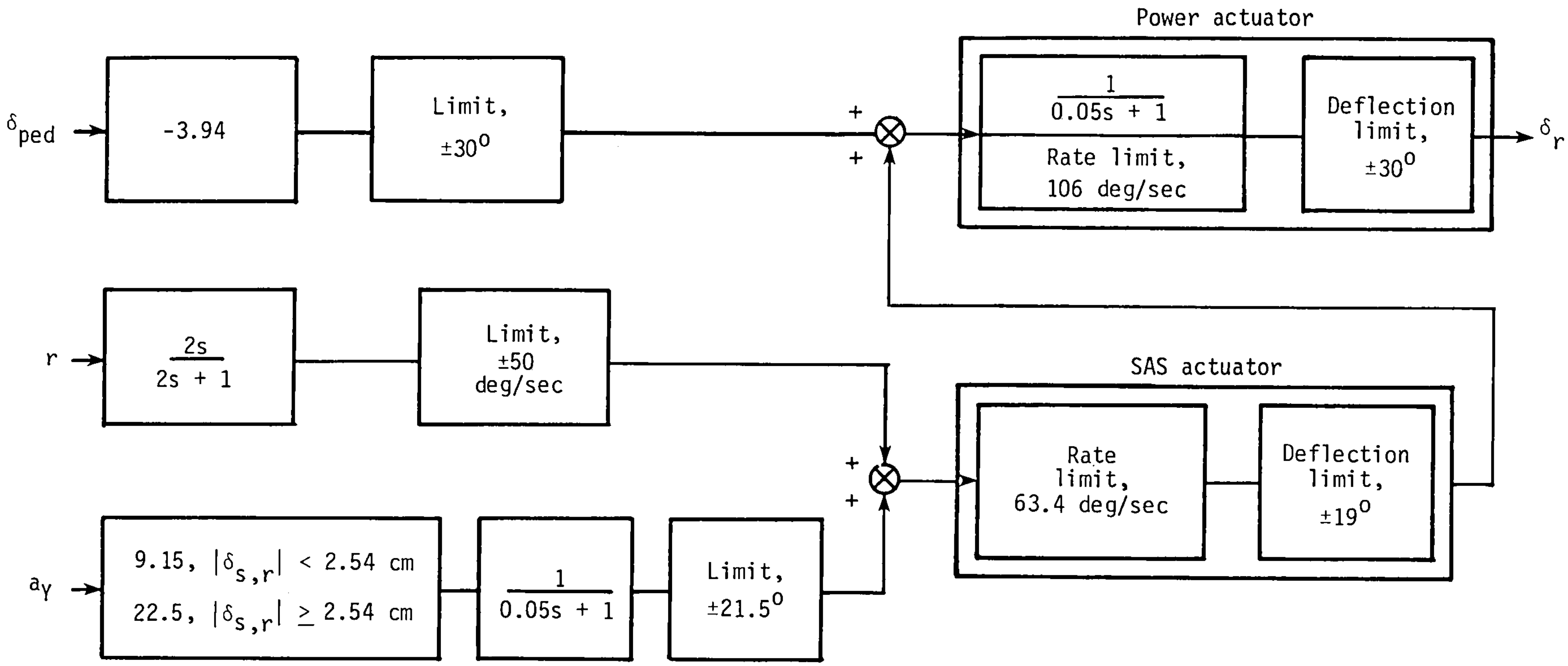


Figure 10.- Schematic diagram of yaw channel of control system A.

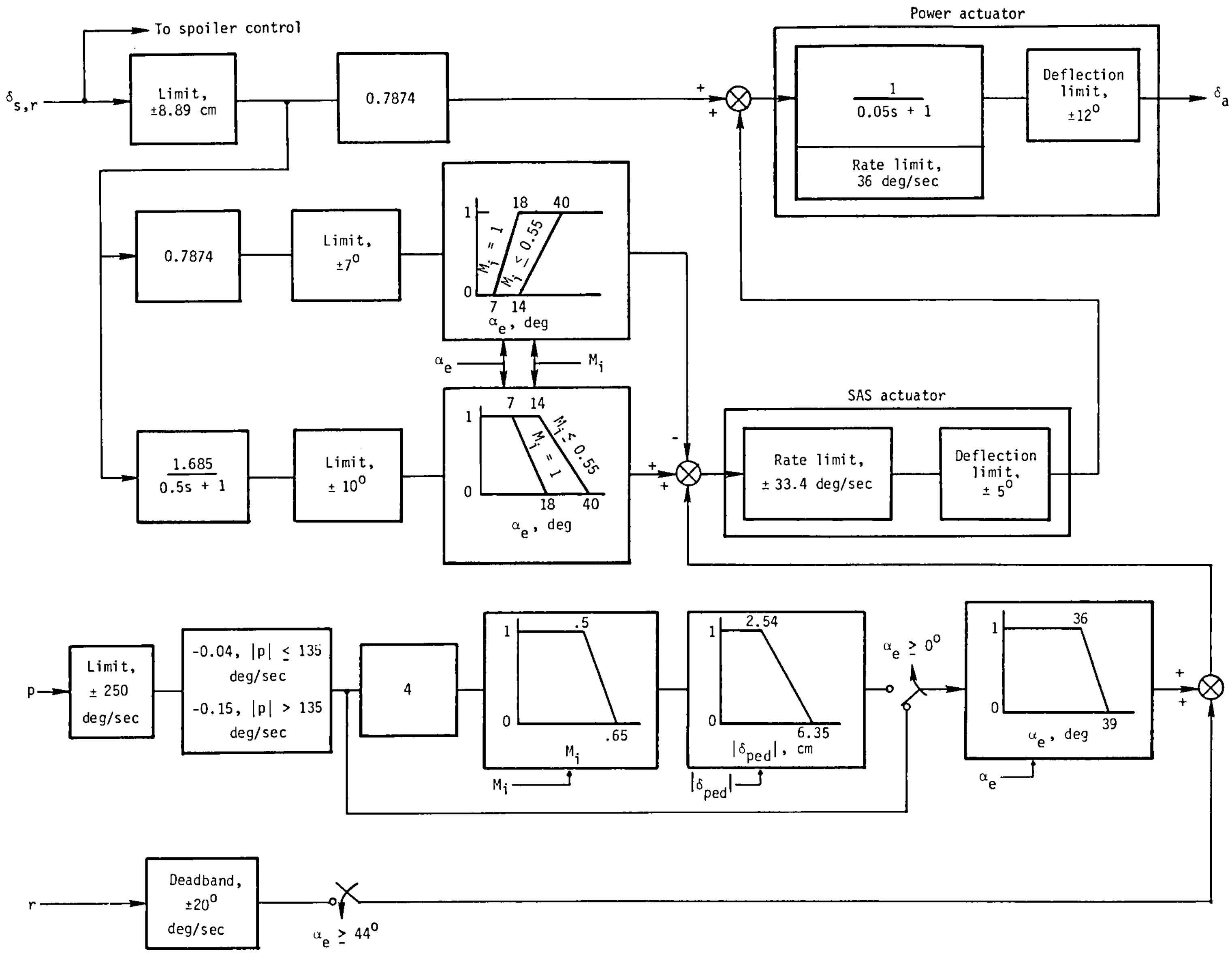


Figure 11.- Schematic diagram of roll channel of control system B.

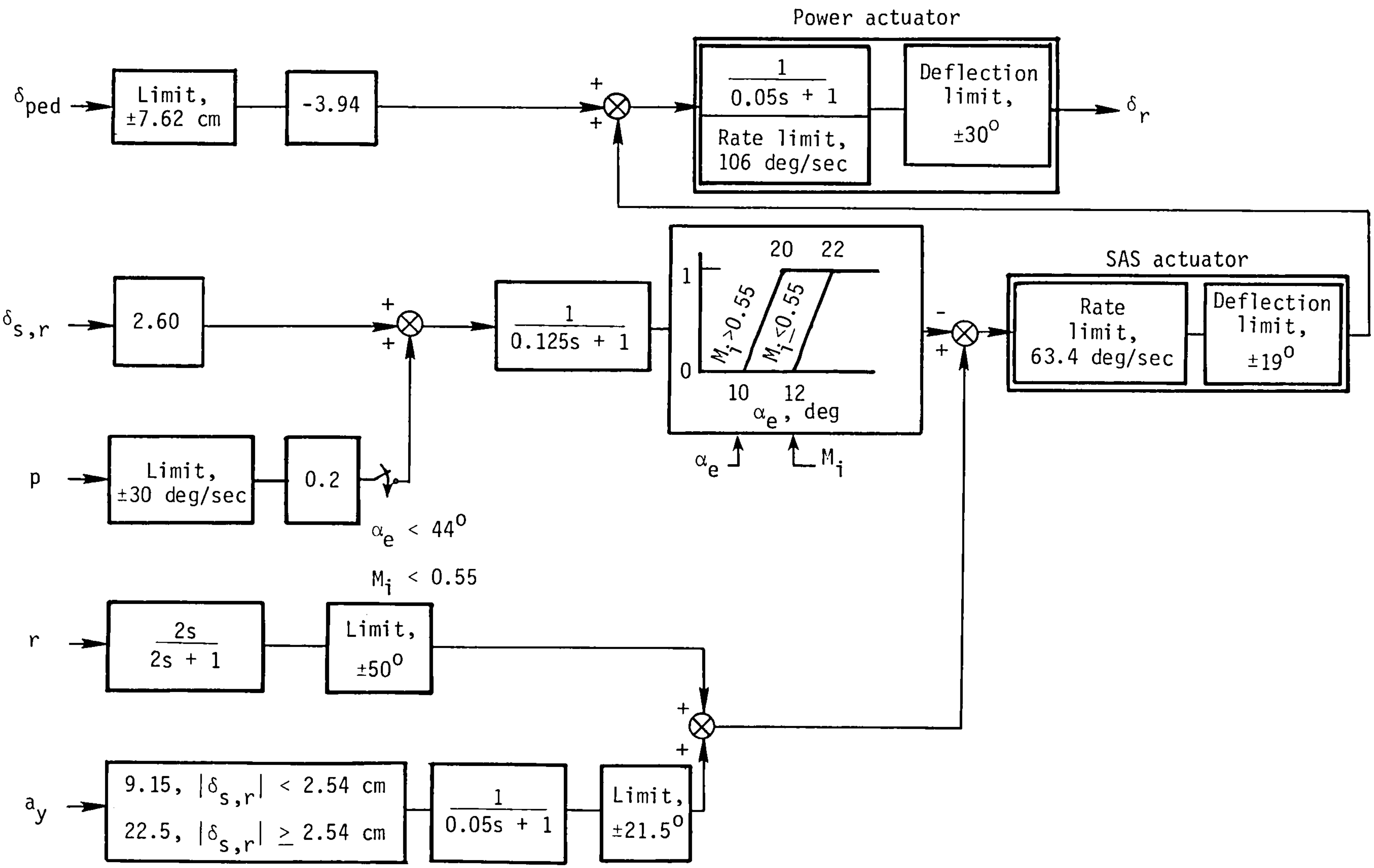


Figure 12.- Schematic diagram of yaw channel of control system B.

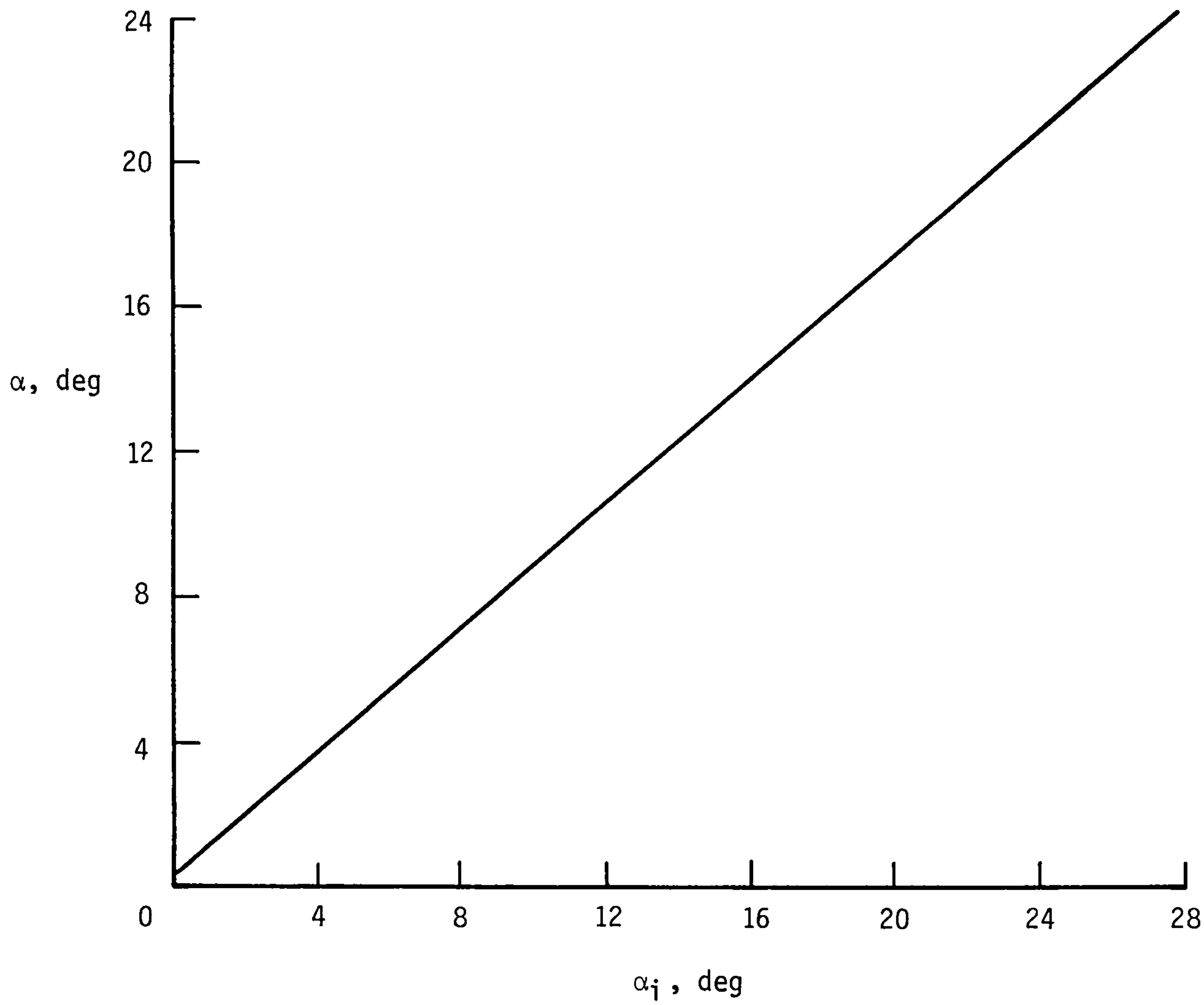


Figure 13.- Relationship of true angle of attack to indicated angle of attack.

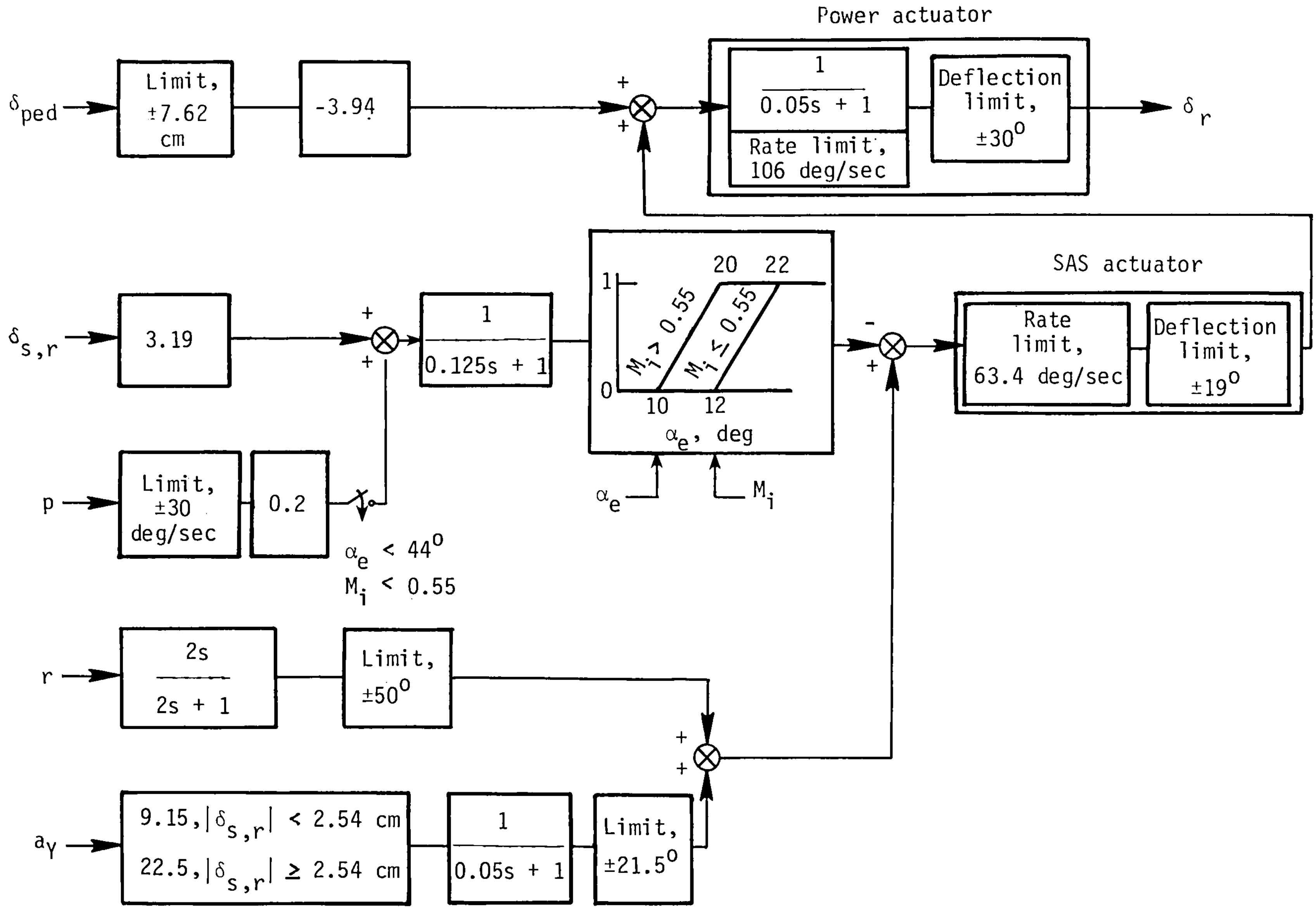


Figure 14.- Schematic diagram of yaw channel of control system C.

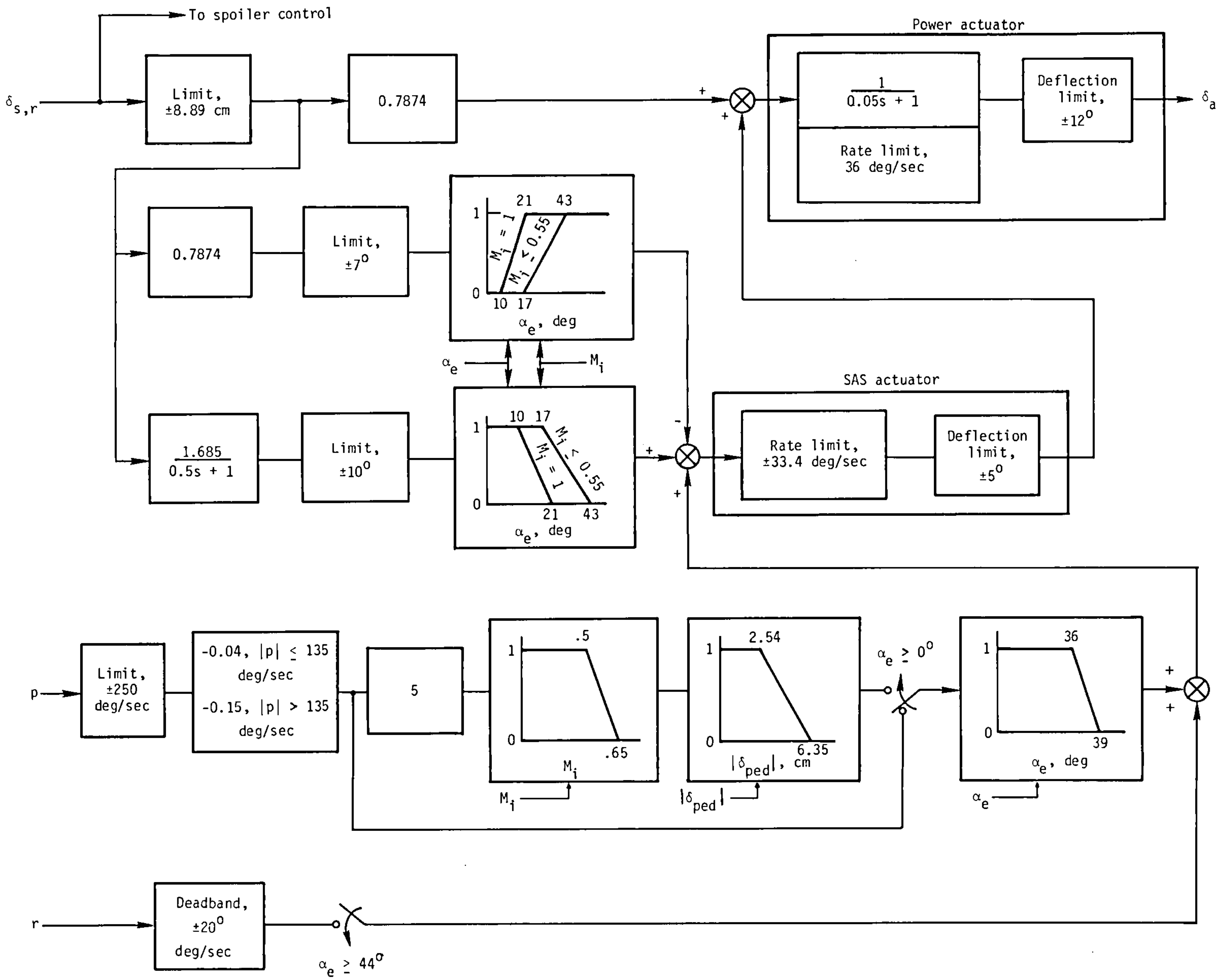


Figure 15.- Schematic diagram of roll channel of control system C.

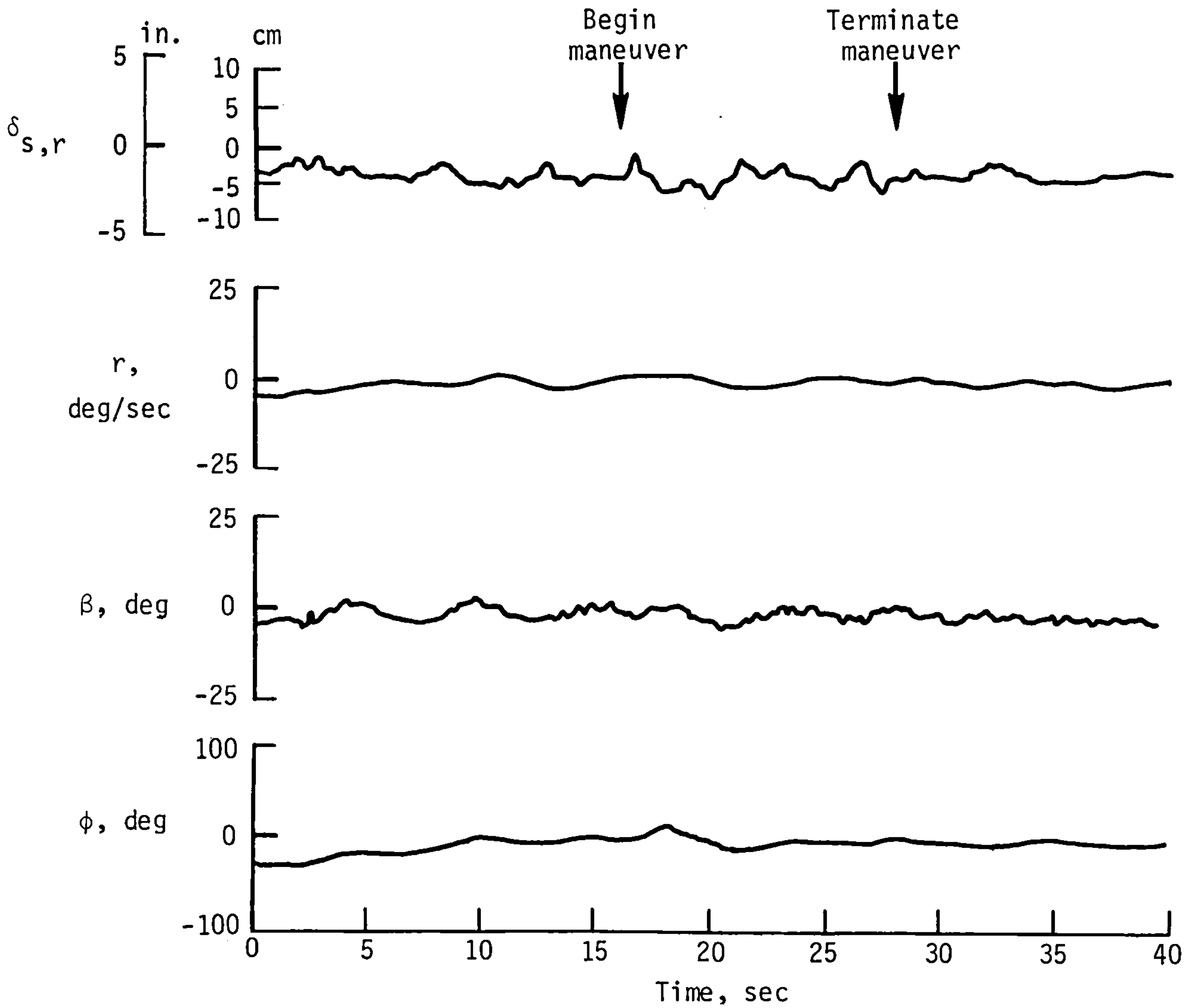


Figure 16.- Lateral offset correction maneuver with control system A.

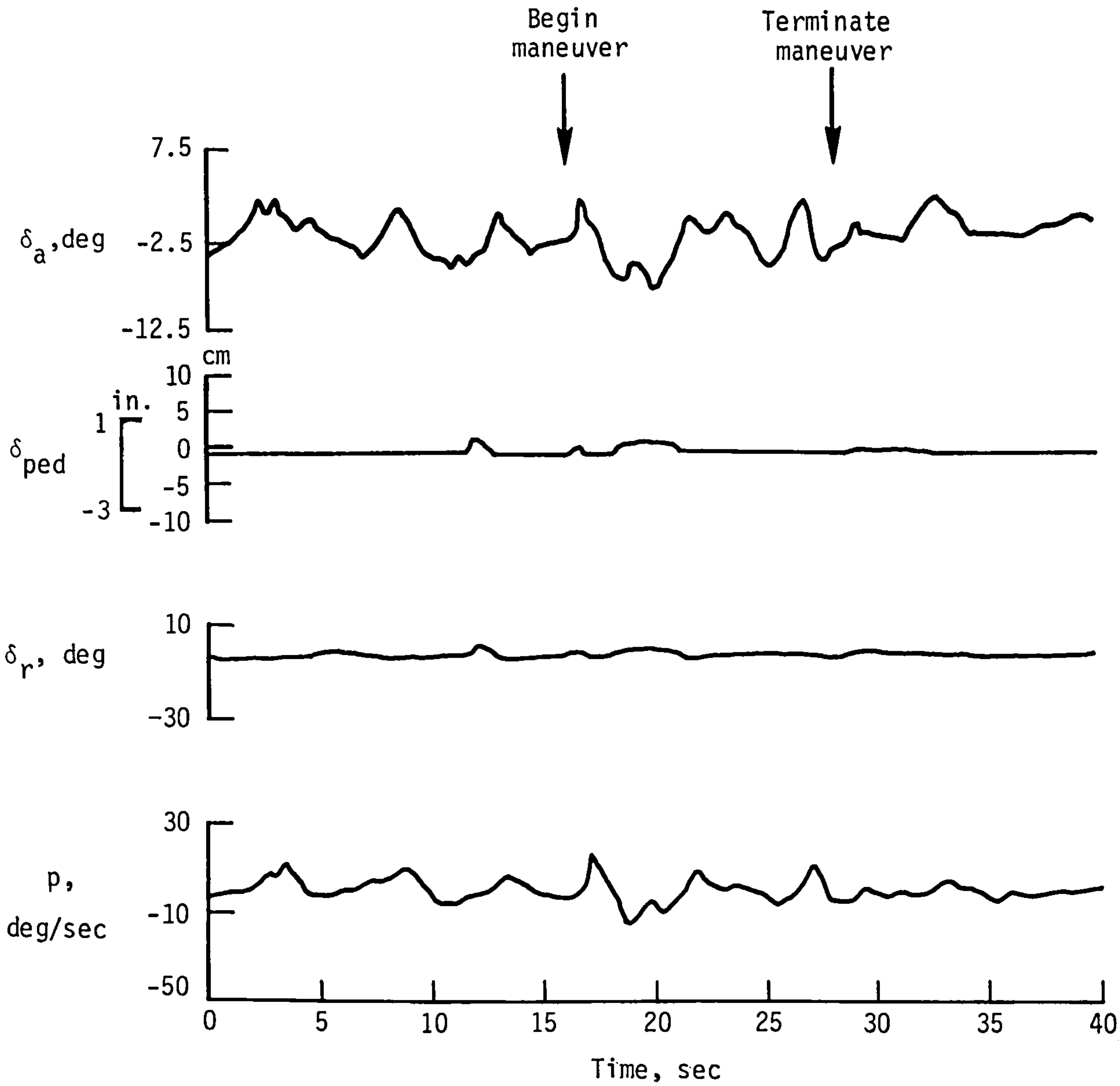


Figure 16.- Continued.

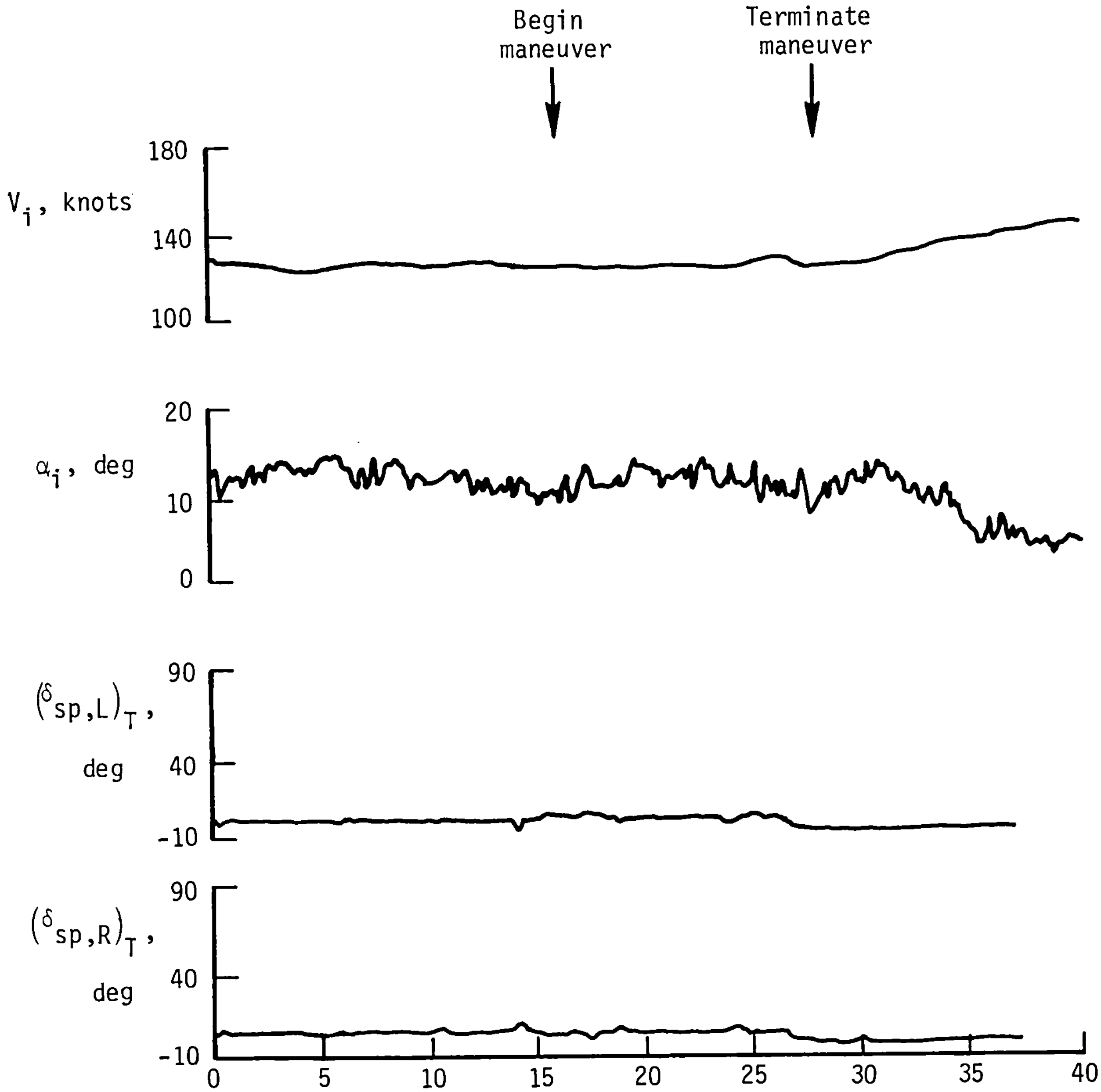


Figure 16.- Concluded.

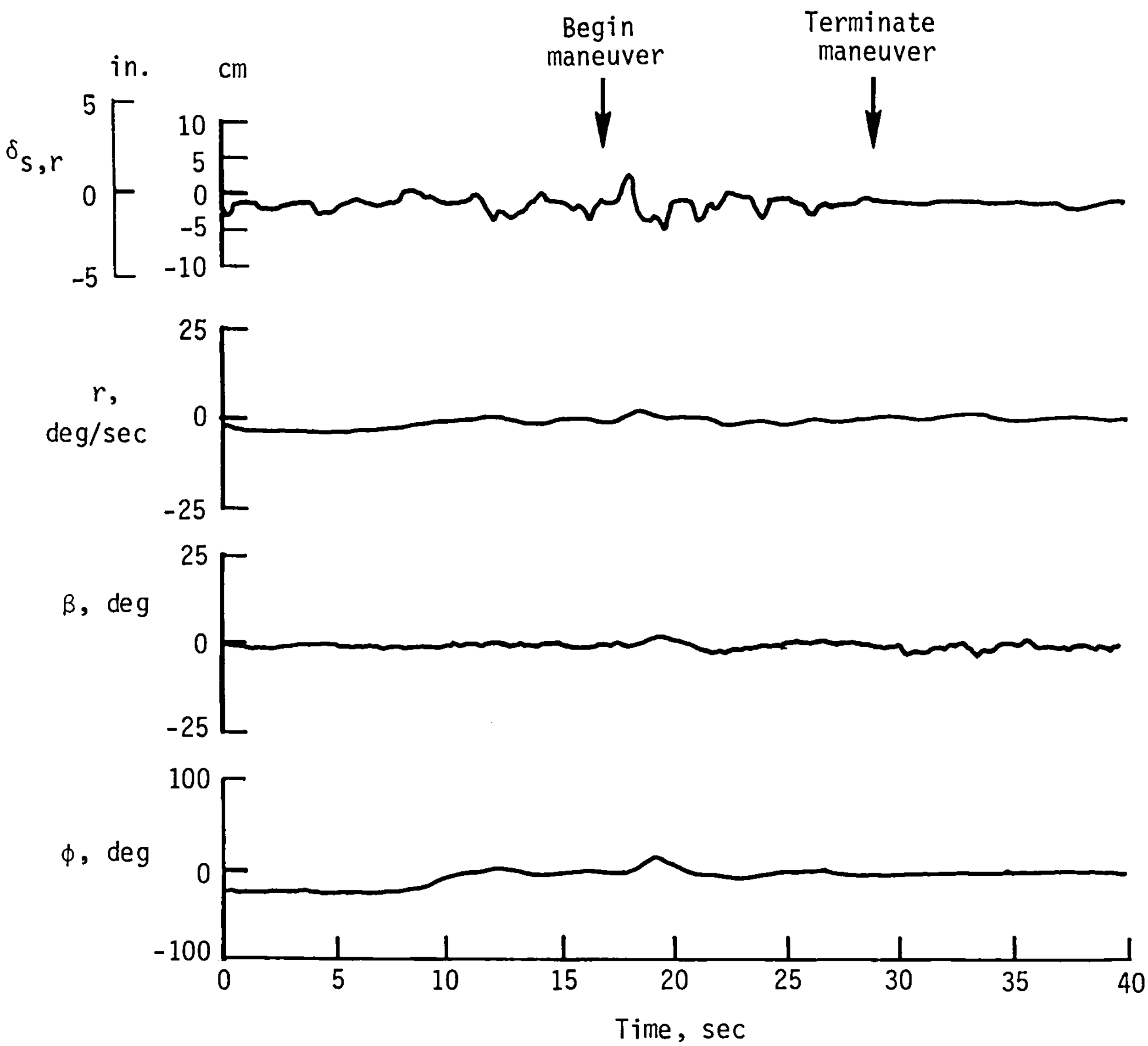


Figure 17.- Lateral offset correction maneuver with control system B.

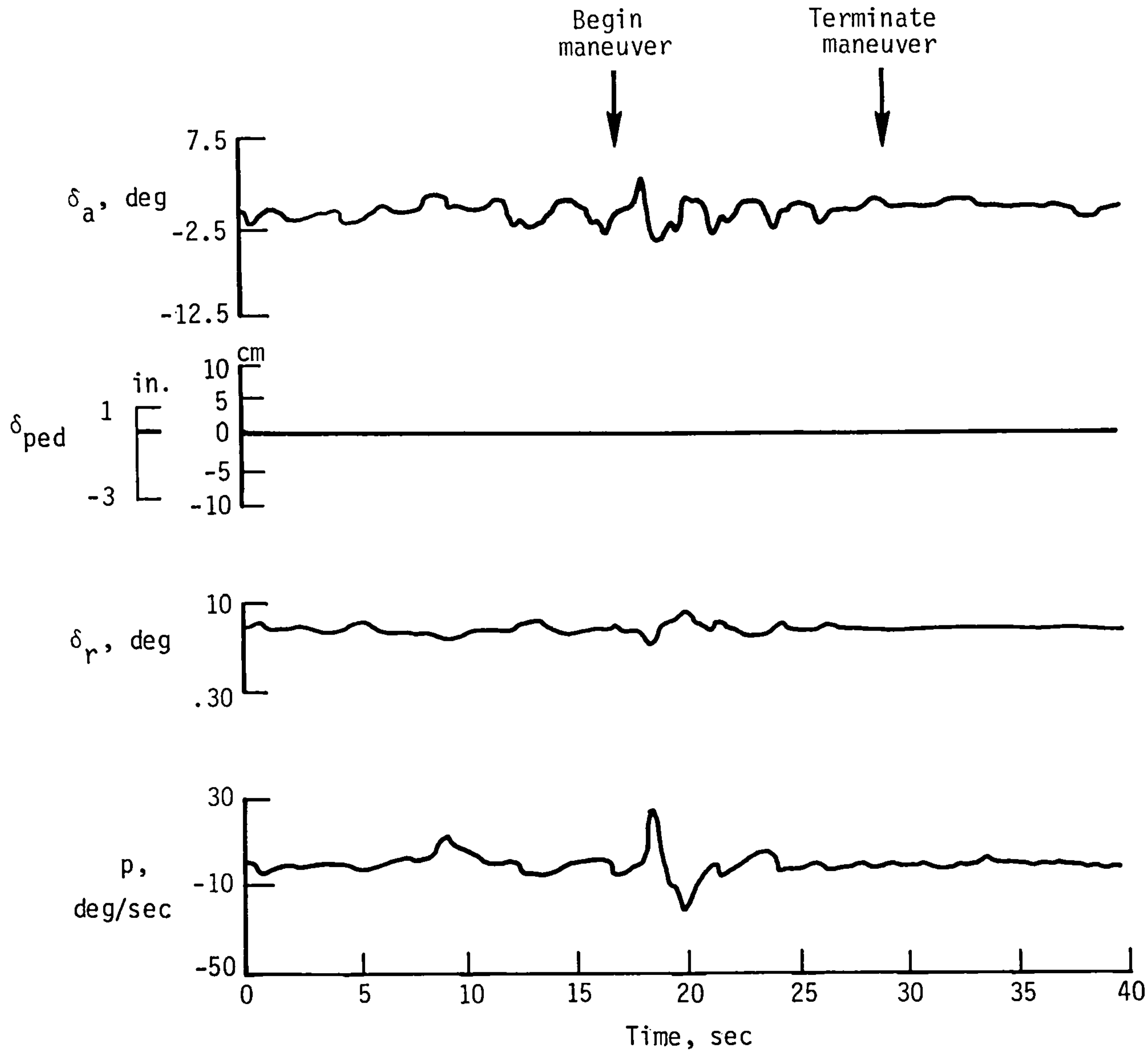


Figure 17.- Continued.

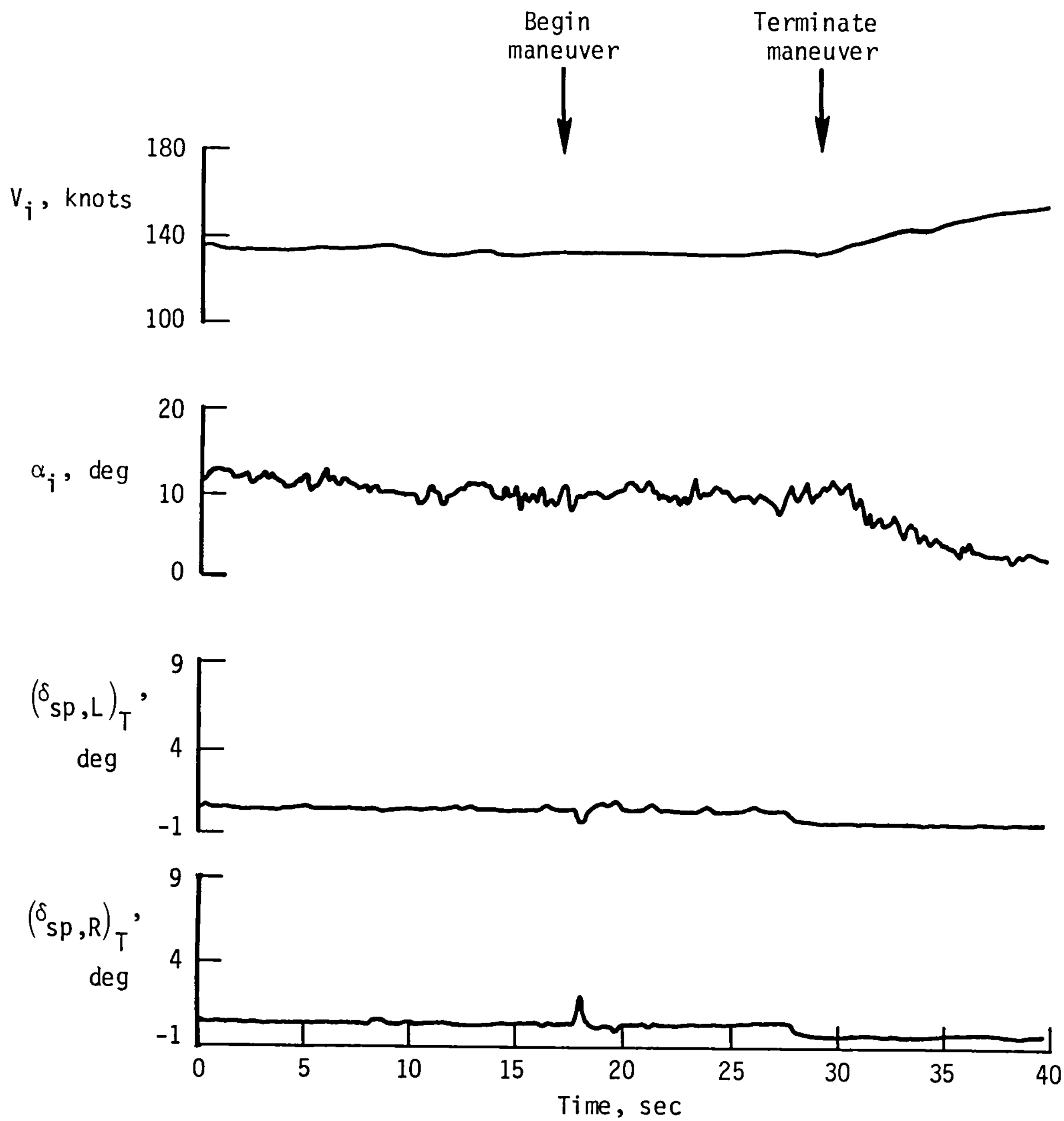


Figure 17.- Concluded.

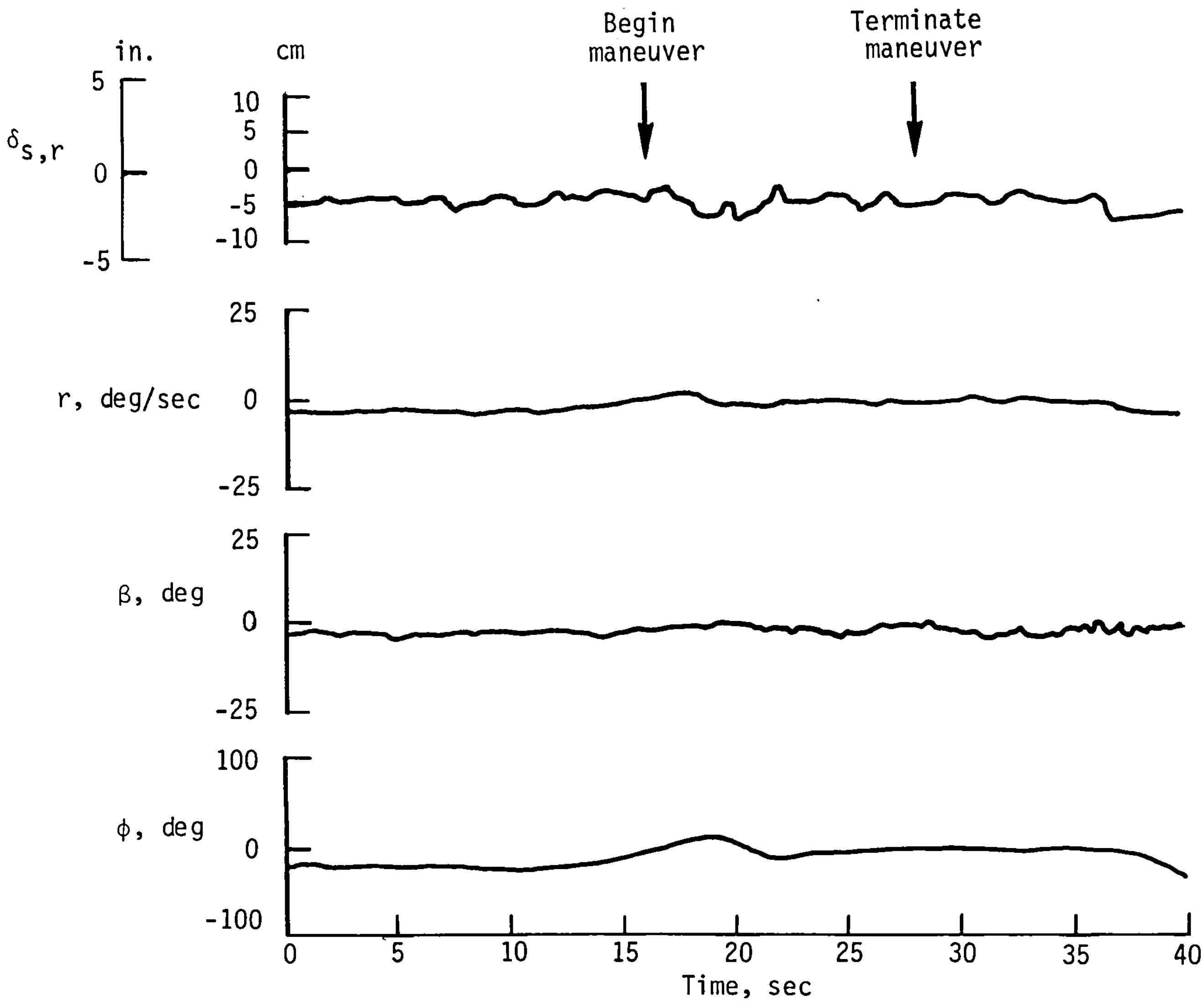


Figure 18.- Lateral offset correction maneuver with control system C.

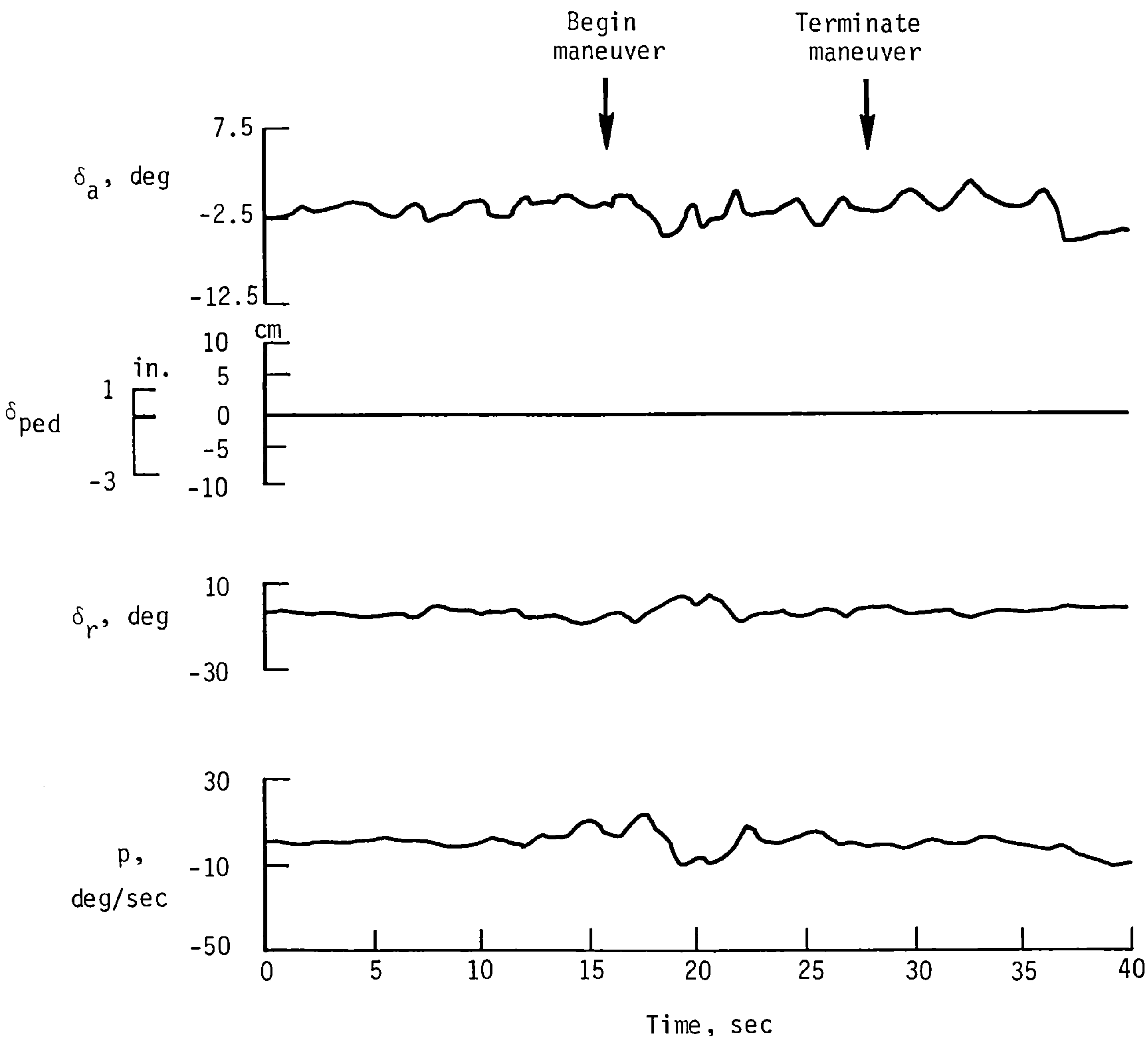


Figure 18.- Continued.

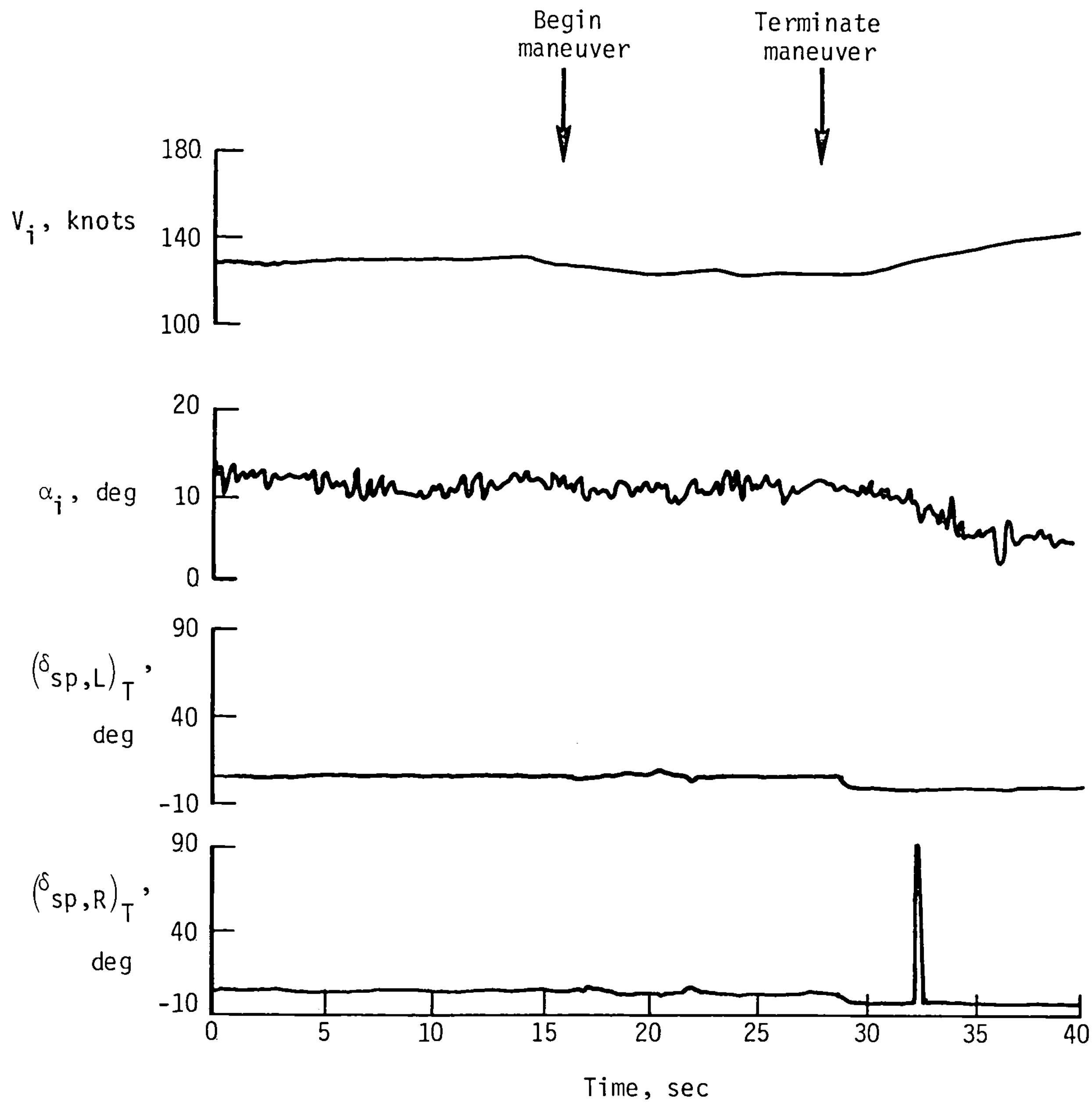


Figure 18.- Concluded.

1. Report No. NASA TM-81972	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle LIMITED EVALUATON OF AN F-14A AIRPLANE UTILIZING AN AILERON-RUDDER INTERCONNECT CONTROL SYSTEM IN THE LANDING CONFIGURATION		5. Report Date December 1981
		6. Performing Organization Code 505-43-13-01
7. Author(s) Wendell W. Kelley and Einar K. Enevoldson		8. Performing Organization Report No. L-14756
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

A flight test was conducted for preliminary evaluation of an aileron-rudder interconnect (ARI) control system for the F-14A airplane in the landing configuration. Two ARI configurations were tested in addition to the standard F-14 flight control system. Results of the flight test showed marked improvement in handling qualities when the ARI systems were used. Sideslip due to adverse yaw was considerably reduced, and airplane turn rate was more responsive to pilot lateral-control inputs. Pilot comments substantiated the flight data and indicated that the ARI systems were superior to the standard control system in terms of pilot capability to make lateral offset corrections and heading changes on final approach.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
F-14A airplane Aileron-rudder interconnect (ARI) Flight controls Flight test Fighter airplane	Unclassified - Unlimited Subject Category 08

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	37	A03

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